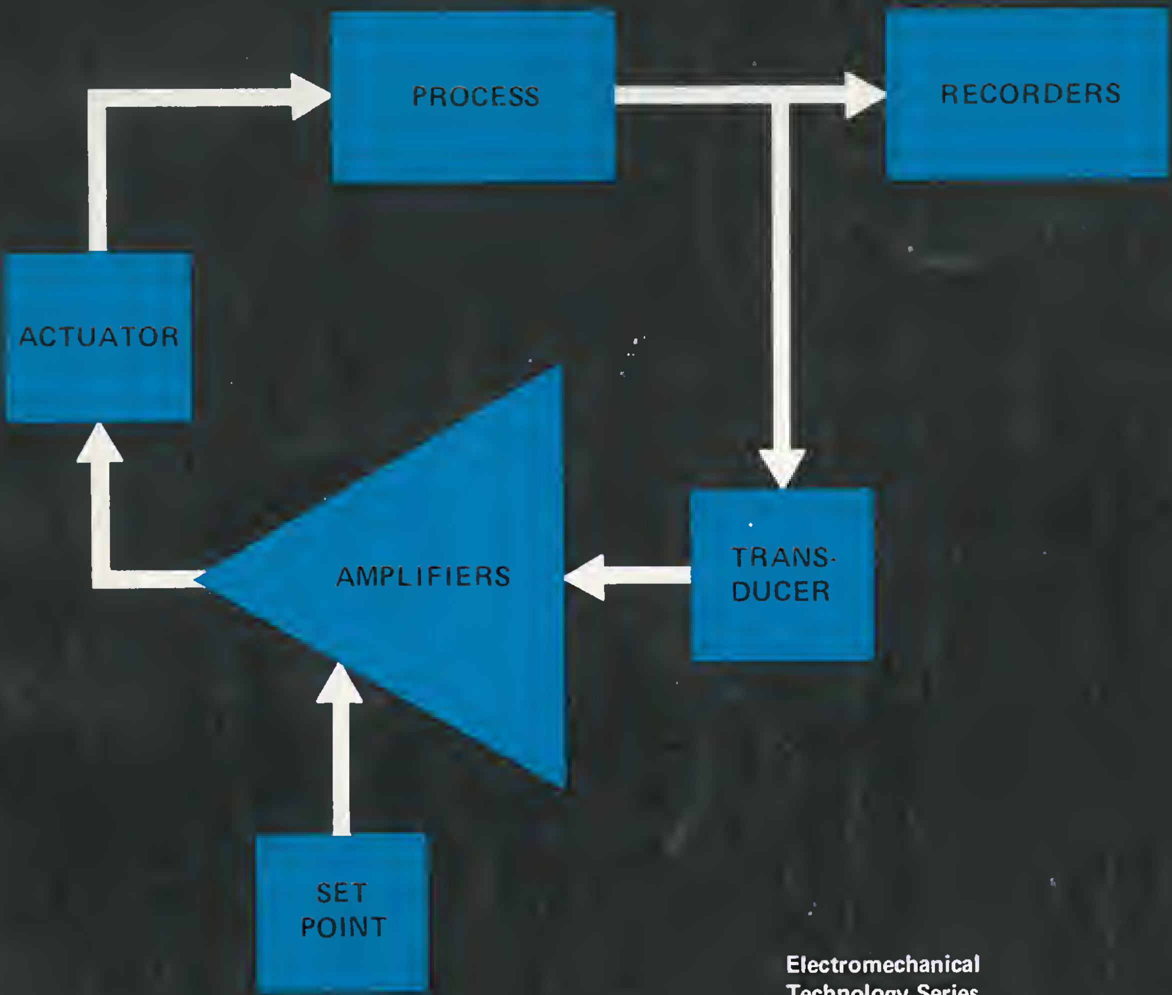
ELECTRO MECHANISMS

AUTOMATIC CONTROLS



Electromechanical
Technology Series
TERC EMT STAFF

DELMAR PUBLISHERS, MOUNTAINVIEW AVENUE, ALBANY, NEW YORK 12205

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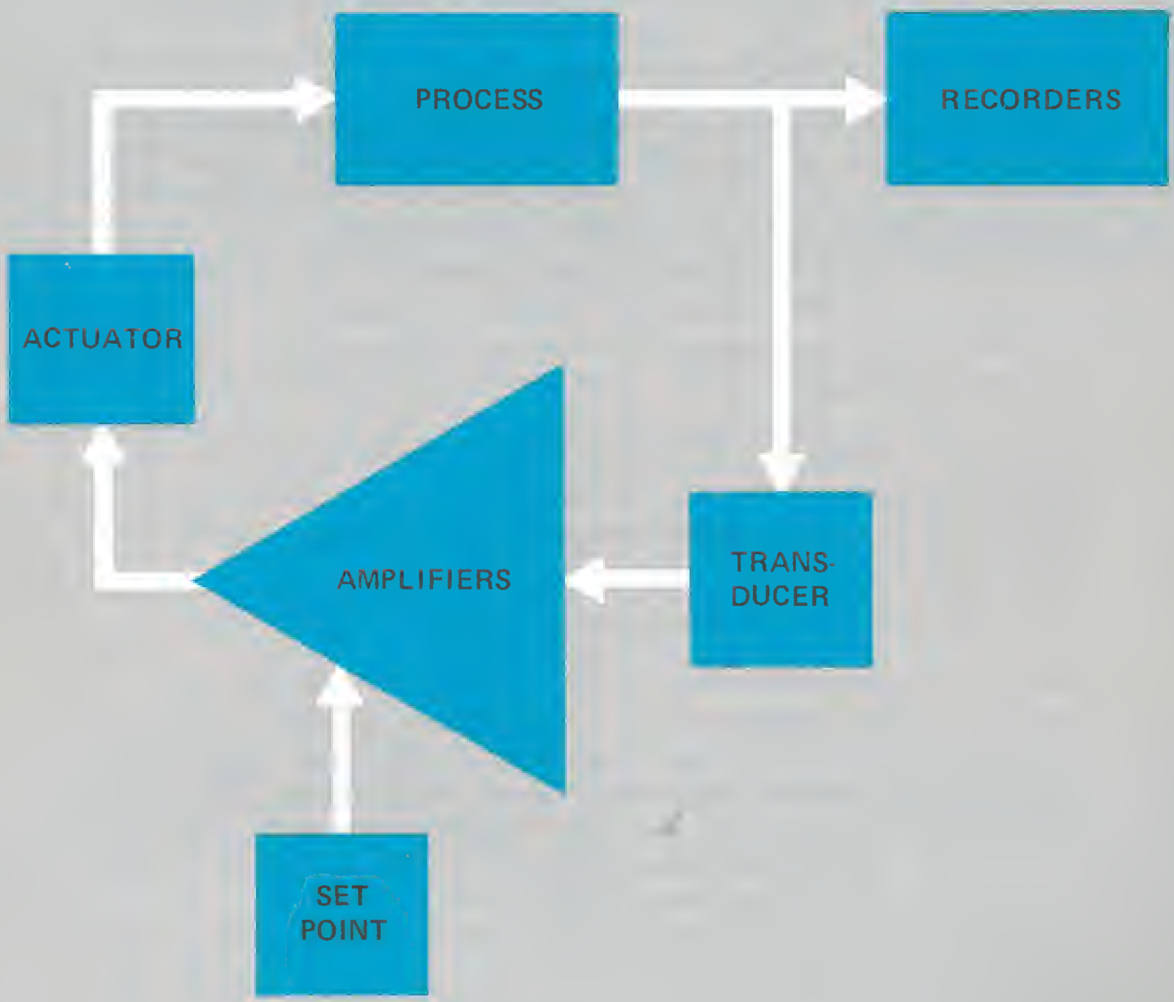

ROY D. BYRD

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Foreword

The marriage of electronics and technology is creating new demands for technical personnel in today's industries. New occupations have emerged with combination skill requirements well beyond the capability of many technical specialists. Increasingly, technicians who work with systems and devices of many kinds — mechanical, hydraulic, pneumatic, thermal, and optical — must be competent also in electronics. This need for combination skills is especially significant for the youngster who is preparing for a career in industrial technology.

This manual is one of a series of closely related publications designed for students who want the broadest possible introduction to technical occupations. The most effective use of these manuals is as combination textbook-laboratory guides for a full-time, post-secondary school study program that provides parallel and concurrent courses in electronics, mechanics, physics, mathematics, technical writing, and electromechanical applications.

A unique feature of the manuals in this series is the close correlation of technical laboratory study with mathematics and physics concepts. Each topic is studied by use of practical examples using modern industrial applications. The reinforcement obtained from multiple applications of the concepts has been shown to be extremely effective, especially for students with widely diverse educational backgrounds. Experience has shown that typical junior college or technical school students can make satisfactory progress in a well-coordinated program using these manuals as the primary instructional material.

School administrators will be interested in the potential of these manuals to support a common first-year core of studies for two-year programs in such fields as: instrumentation, automation, mechanical design, or quality assurance. This form of *technical core* program has the advantage of reducing instructional costs without the corresponding decrease in holding power so frequently found in general core programs.

This manual, along with the others in the series, is the result of six years of research and development by the *Technical Education Research Centers, Inc.,* (TERC), a national nonprofit, public service corporation with headquarters in Cambridge, Massachusetts. It has undergone a number of revisions as a direct result of experience gained with students in technical schools and community colleges throughout the country.

Maurice W. Roney

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Preface

Technology, by its very nature, is a laboratory-oriented activity. As such, the laboratory portion of any technology program is vitally important. These materials are intended to provide a meaningful experience with automatic controls for students of modern technology.

The topics included provide exposure to basic principles of control systems, transducers, actuators, amplifiers, and controllers.

The sequence of presentation chosen is by no means inflexible. It is expected that individual instructors may choose to use the materials in other than the given sequence.

The particular topics chosen for inclusion in this volume were selected primarily for convenience and economy of materials. Some instructors may wish to omit some of these exercises or to supplement some of them to better meet their local needs.

The materials are presented in an action-oriented format combining many of the features normally found in a textbook with those usually associated with a laboratory manual. Each experiment contains:

1. An INTRODUCTION which identifies the topic to be examined and often includes a rationale for doing the exercise.
2. A DISCUSSION which presents the background, theory, or techniques needed to carry out the exercise.
3. A MATERIALS list which identifies all of the items needed in the laboratory experiment. (Items usually supplied by the student such as pencil and paper are not included in the lists.)
4. A PROCEDURE which presents step-by-step instructions for performing the experiment. In most instances the measurements are done before calculations so that all of the students can at least finish making the measurements before the laboratory period ends.
5. An ANALYSIS GUIDE which offers suggestions as to how the student might approach interpretation of the data in order to draw conclusions from it.
6. PROBLEMS are included for the purpose of reviewing the reinforcing the points covered in the exercise. The problems may be of the numerical solution type or simply questions about the exercise.

Students should be encouraged to study the test material, perform the experiment, work the review problems, and submit a technical report on each topic. Following this pattern, the student can acquire an understanding of, and skill with, basic electric circuits that will be extremely valuable on the job. For best results, these students should have a sound background in technical mathematics (algebra, trigonometry, and introductory calculus.)

These materials on basic control systems comprise one of a series of volumes prepared for technical students by the TERC EMT staff at Oklahoma State University, under the direction of D.S. Phillips and R.W. Tinnell. The principal author of these materials was Roy D. Byrd.

An *Instructor's Data Guide* is available for use with this volume. Mr. R.D. Byrd and Mr. D.A. Yeager were responsible for testing the materials and compiling the instructor's data book for them. Other members of the TERC staff made valuable contributions in the form of criticisms, corrections, and suggestions.

It is sincerely hoped that this volume as well as the other volumes in this series, the instructor's data books, and the other supplementary materials will make the study of technology interesting and rewarding for both students and teachers.

THE TERC EMT STAFF

Contents

The author and editorial staff at Delmar Publishers are interested in continually improving the quality of this instructional material. The reader is invited to submit constructive criticism and questions. Responses will be reviewed jointly by the author and source editor. Send comments to:

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Box 5087
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experiment 1 *INTRODUCTION TO AUTOMATION*

INTRODUCTION. The ever-increasing use of automatic control systems in industry requires large numbers of suitably trained electromechanical technicians. In this experiment the basic principles of a control system will be investigated.

DISCUSSION. A simple control system is a device which allows a human operator to control the flow of energy to a machine or process in such a manner as to achieve a desired performance. A person's eyes, ears and the ability to feel are used to note the effect, and the hands or feet then control the application of energy.

Industrial control systems, usually, fall into two general categories: open-loop and closed-loop systems. In an open-loop system, the controlling device operates independently of the process variable it controls. In a closed-loop system, the process variable is constantly monitored and kept at a predetermined value automatically. Closed-loop systems are termed automatic control systems and must employ some type of feedback.

A simple example of an open-loop system is shown in figure 1–1. The room heater is a heat source used to control the temperature in the room. If the temperature in the room is below the comfort level, the heater is turned on manually with the switch. When the room temperature rises to the comfort level or above, the switch is manually turned off. In this process, the temperature is the controlled variable and the controlling device is the switch. The controlled device is the heat source. The temperature in the room does not affect the operation of the switch. Since the controlling device operates independently of the *process variable,* the system can be classified as an open-loop system. If the temperature in the room is to be kept at some predetermined value, a temperature indicator must be employed and a switch operated to turn the heat on and off. The operator can control the process variable by operating the switch in such a manner as to keep the temperature at the predetermined value.

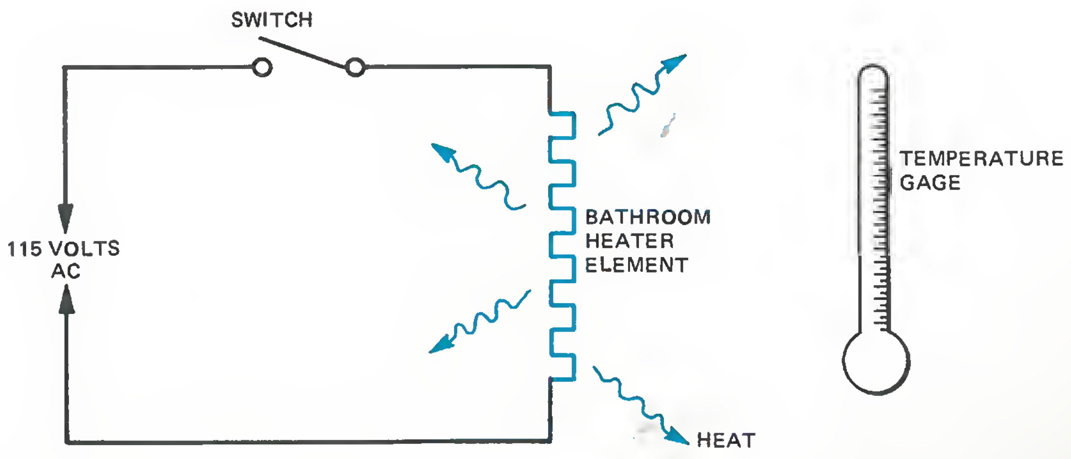


Fig. 1-1 Simple Open-Top Control System

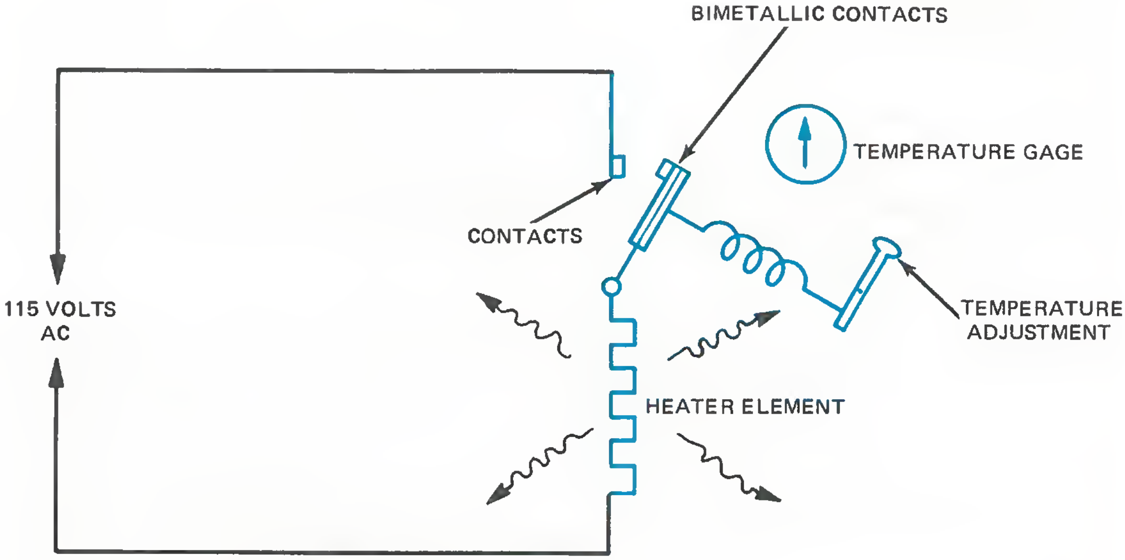


Fig. 1-2 Simple Closed-Loop System

An example of a closed-loop system is shown in figure 1-2. The room has a thermostat-controlled heating system. If the temperature in the room falls below a desired level, the thermostat contacts close and the heater is turned on. When the temperature in the room rises above the desired level, the thermostat contacts open and the heater is turned off. In this process, the temperature is the controlled variable and the controlling device is the thermostat. The thermostat continuously monitors the actual room temperature and compares it with the desired value, termed the *set-point*, in order to keep the room temperature at some predetermined value automatically. In this automatic control system, the actual room temperature (process variable) is measured by the bimetallic strip (sensor) and compared to the predetermined desired room temperature (set-point). Any difference (*error* or *deviation*) between the actual temperature and desired temperature will cause the thermostat contacts (*controller*) to either open or close. The opening and closing of the contacts controls the amount of heat delivered by the heater element (actuator) in maintaining the desired temperature.

The first automatic control system was probably invented by James Watt in the late 18th century. He employed a mechanical device, the fly-ball governor, to control the speed of a steam engine automatically. The system is shown in figure 1-3.

This simple control system exhibits all the characteristics of an automatic control system. As the engine speed increases, the drive shaft in figure 1-3 turns faster, thus turning the governor shaft faster. As the speed of the governor shaft increases, the balls of the governor rotate faster and move outward due to centrifugal force. As the balls of the governor move outward, the control coupling moves up the governor shaft. As the control coupling moves up the governor shaft, it moves the control valve toward the closed direction, reducing the amount of steam to the driving cylinder. The engine slows because of the decrease in steam admitted to the driving cylinders. As the engine slows, the fly-balls will move inward causing an increase in steam admitted to the driving cylinders. This action continues until the speed of the engine drive shaft and the position of the fly-balls are bal-

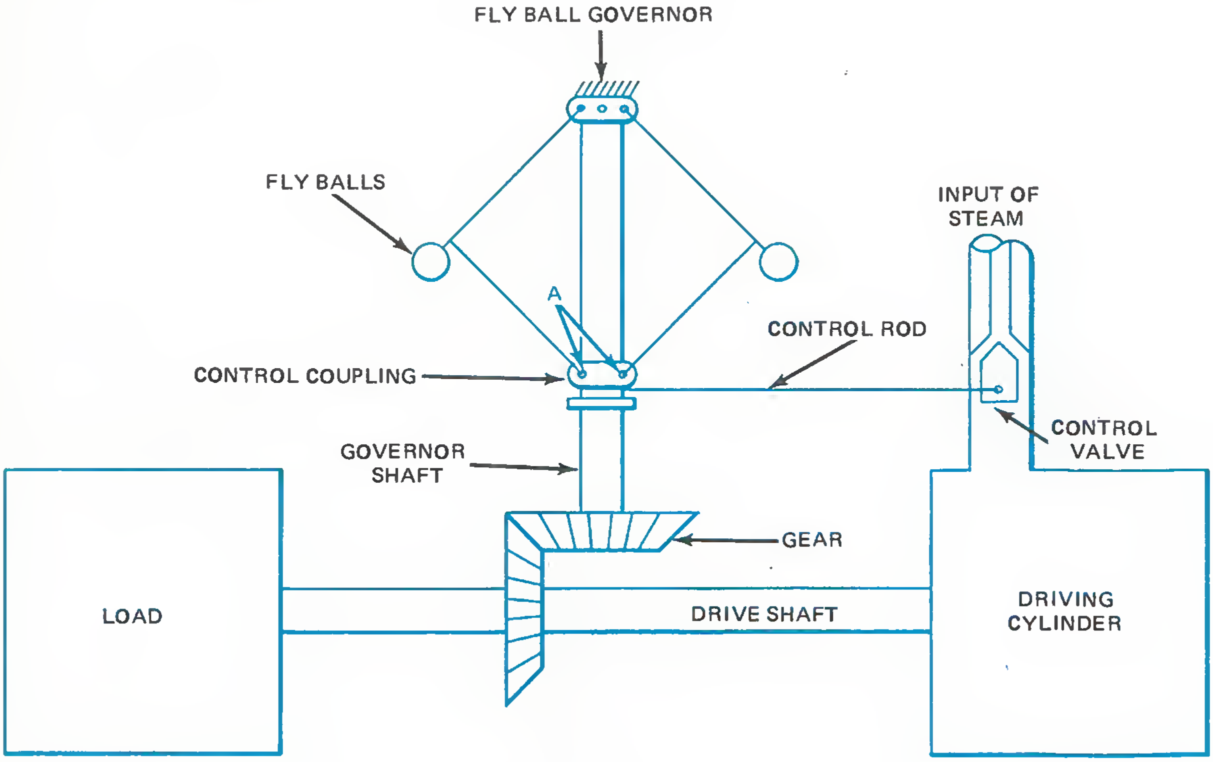


Fig. 1-3 Watt's Automatic Control System

anced. This set speed can be adjusted by moving the point where the governor is locked to the shaft. To increase speed, the logic point is placed higher on the shaft. Lowering the point decreases the space. This system is termed an automatic control system, since it automatically controls the speed of the engine drive shaft.

From this simple explanation of the fly-ball governor, it is easy to determine the basic necessities required in automatic control systems.

First, the variable to be controlled must be identified. In the case of the fly-ball governor it is the speed of the drive shaft. Second, a sensing device must be employed to measure the variable to be controlled. In this case it is the fly-ball governor. Third, a reference or set-point with which the actual controlled function can be compared is employed. In the case of the fly-ball governor, it is point A where the governor is locked to the shaft. Fourth, a controller is needed that compares the actual, controlled function with the reference element or set-point and generates corrective information. In the case of the fly-ball governor, it is the control coupling position. Fifth, an actuator must act on the corrective information supplied by the controller to control the process variable. In the case of the fly-ball governor, it is the control valve that performs this service.

An automatic control system consists of four main elements: (1) a sensing device, (2) a set-point or reference element, (3) a controller, and (4) an actuator. These elements are fundamental to any automatic process. A block diagram of an automatic control system is shown in figure 1-4.

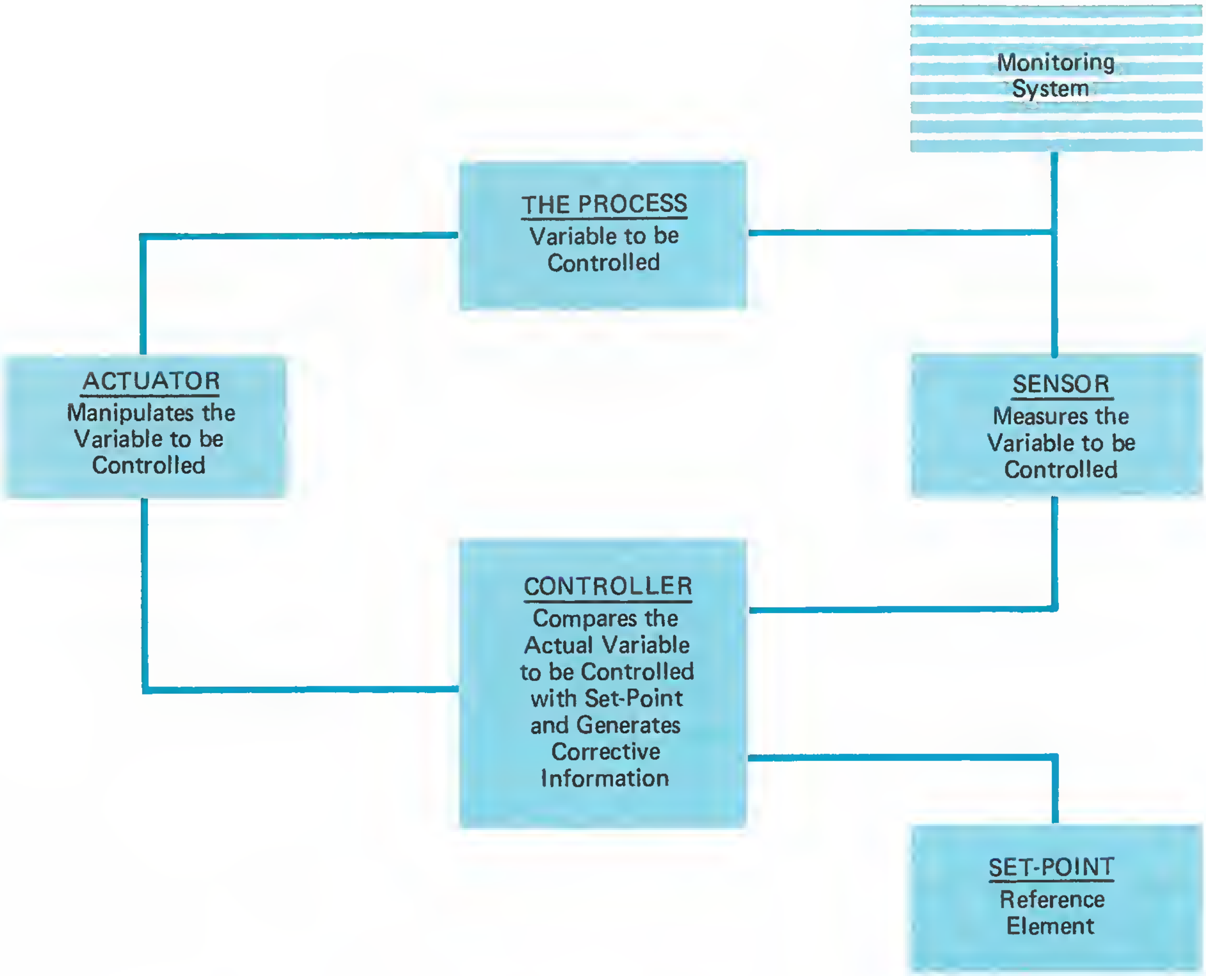


Fig. 1-4 Block Diagram of an Automatic Control System

In practice, modern industry requires constant monitoring of the process or system variable to see that it conforms to a predetermined value. Automatic recorders or indicators are employed which monitor each variable and indicate and sometimes record its value.

The employment of devices to control automatically one or more functions in a machine or an industrial process is called automation. Generally, automation is referred to as an automatic control system. Automatic control is the employment of a device to automatically control a single function or process.

Automation has many advantages, among which are:

1. A more consistent product or process.
2. Accuracy and consistency in controlling the speed of rotating shafts and positioning of moving parts.

The basic principles of automatic control systems, whether they control a process or a machine, are essentially the same. They involve measurement, comparison and adjustment of energy flow so that deviation is reduced to a minimum.

MATERIALS

- 1 Stroboscope
- 1 Motor, 28 volt DC, 1/100 HP
- 1 Generator, permanent magnet, approximately 3.8 volts/100 RPM
- 2 Power supply, 0–40 volts
- 1 Transistor, HEP 232 or equivalent
- 1 Transistor, HEP 254 or equivalent
- 1 Transistor, HEP 53 or equivalent
- 1 Potentiometer, 0-10 kΩ
- 2 Resistors, 1 kΩ 1/2W
- 1 Resistor, 10 kΩ 1/2W
- 1 Resistor, 2 kΩ 1/2W
- 1 Shaft, approximately 4 inches in length
- 3 Adapter couplings
- 1 One-ounce weight
- 1 Lever arm, 3 inches in length
- 1 Heat sink - HEP 232
- 1 Heat sink - HEP 254

PROCEDURE

1. Assemble the motor, generator and torque load as shown in figure 1-5.
2. Construct the experimental circuit as shown in figure 1-6.

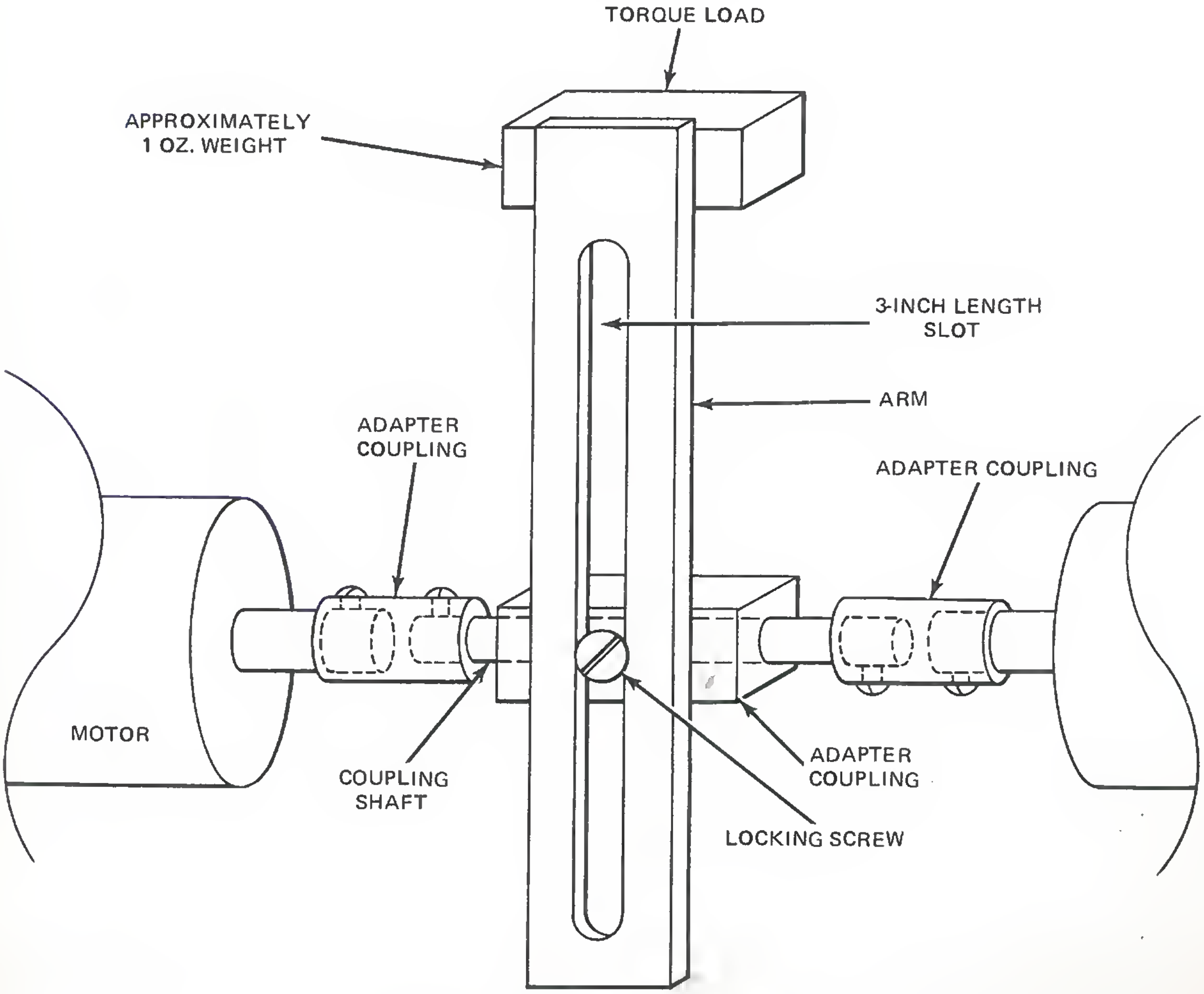


Fig. 1-5 Mechanical Coupling

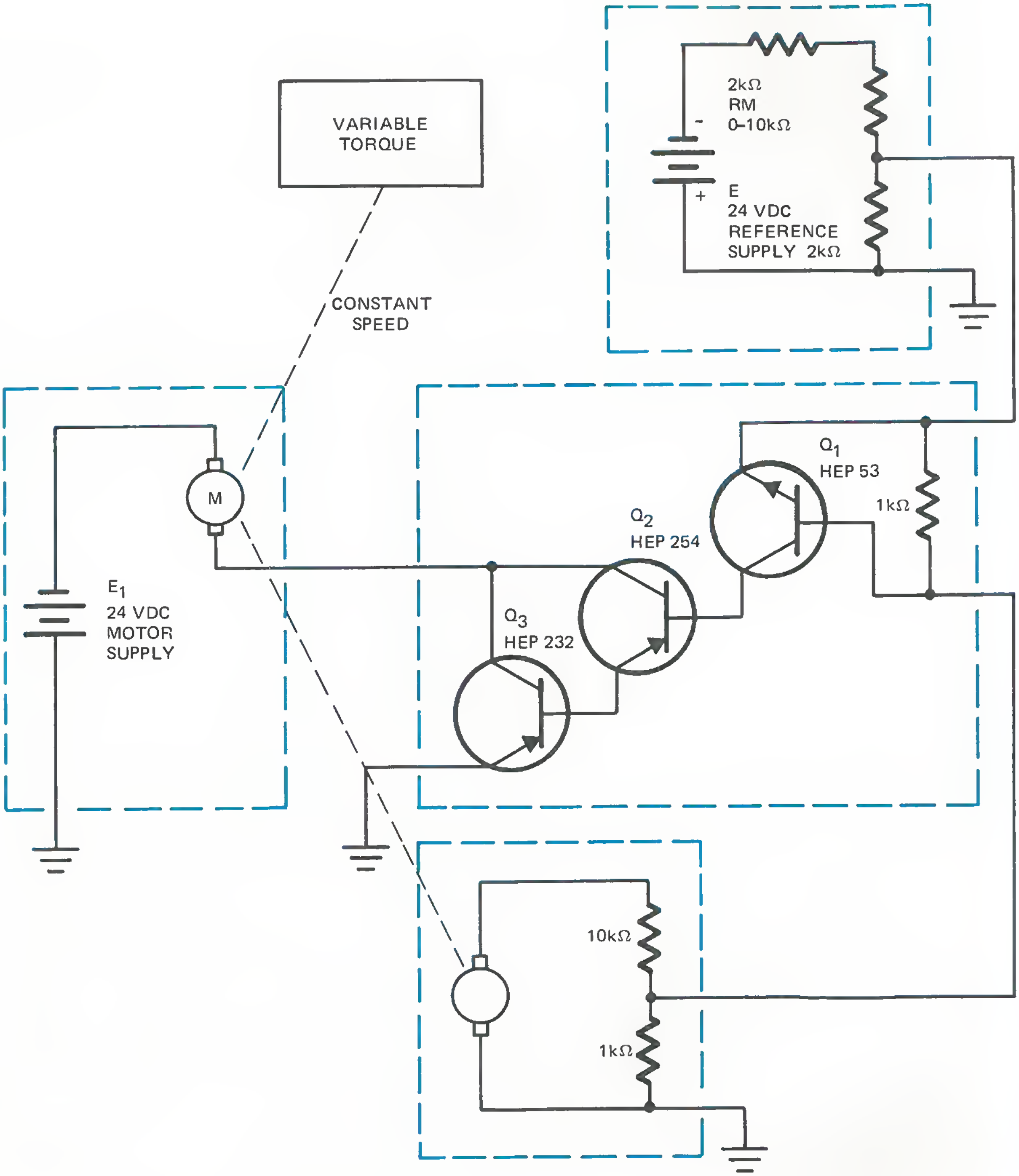


Fig. 1-6 Experimental Setup

3. Set the torque load for minimum by moving the arm until the one-ounce weight is as close as possible to the shaft. Secure the arm in this position with the locking screw. Measure the distance from the center of the shaft to the center of the torque load. Record this distance in Data Table, figure 1–7 as R.

4. Turn the power supplies on and adjust each voltage to 24 volts.
5. Adjust RM until the speed of the motor, measured with the stroboscope, is 1000 RPM.

   Note: Do not change setting of RM for remainder of the tests.
6. Turn the motor power supply off.
7. Set the torque load to a distance of 1.5 inches. This distance is measured from the center of the torque load.
8. Turn the motor power supply on.
9. Measure the speed of the motor with the stroboscope. Record this measurement in the Data Table as S_a.
10. Repeat steps 6, 7, 8 and 9 for a maximum torque load. Measure and record the speed S_a and the distance R in the Data Table.
11. Adjust the motor supply to zero volts. Do not turn if off. Disconnect the lead from the negative terminal of the generator.
12. Disconnect the lead connecting the motor to the collectors of Q_2 and Q_3 at the collector junction. Connect this lead from the motor to the positive side of the power supply.
13. Set the torque load to minimum as in step 3.
14. Gradually increase the voltage of the motor power supply until the motor speed, measured with the stroboscope, is 1000 RPM.
15. Repeat steps 6, 7, 8, 9 and 10 and record these data as S_o in the data table.
16. Calculate the approximate torque in inch-ounces delivered to the load. The load torque is the product of the load weight and the radius. The load weight is one ounce and the radius is the distance R recorded in the data table. Enter these data in Data Table as T.
17. Calculate the percent of change in speed with increasing load. The percent of change is

$$\%\ \text{Change} = \frac{1000\text{-}S}{S} \times 100$$

Enter these data in the table.

R inches	S_a RPM	S_o RPM	T in.-oz	% Change in S_a	% Change in S_o
	1000	1000		0	0
1.50			1.50		

Fig. 1-7 The Data Table

PROBLEMS

1. Draw a block diagram of an open-loop system used to control the water level in a city water tower.
2. Draw a block diagram of a closed-loop system used to automatically control the water level in a city water tower.
3. Identify two systems where automatic control of a machine is employed.
4. Identify two systems where automatic control of a process is employed.
5. What are some advantages of using automatic control systems?

experiment 2 SENSING DEVICES

INTRODUCTION. In order to control a machine or a process automatically, the state or condition of the variable to be controlled must be known. In this experiment some common detecting elements, termed *sensors* or transducers, will be investigated.

DISCUSSION. In an automatic control system, the whole system relies on a sensing element, called a sensor or a transducer, which senses the condition, state, or value of the variable to be controlled and produces an output which reflects this condition, state, or value. In the human body, the ability to hear, feel, see, smell and taste is used to sense the condition, state, or value of the body conditions and an output is produced for transmission to the brain. The brain compares this signal with some predetermined reference and, if necessary, actuates the proper response system

Generally, the sensing device used in an automatic control system is called a transducer. A transducer senses the condition, state, or value of the process variable and transforms a portion of its energy into an output of some type. The output of the transducer is compared with a predetermined value (set-point) to determine if a difference (error) exists. If an error exists, the system must initiate the necessary corrective action to reduce this error to zero.

An example of a transducer is shown in figure 2-1. This transducer is a thermistor bead made of metallic oxide, which exhibits a high negative-temperature characteristic. If the temperature of the thermistor bead increases, its resistance decreases. Should the temperature of the bead decrease, its resistance would increase. A typical thermistor bead resistance will double for every 10°C decrease in temperature. Since the thermistor bead senses temperature and produces an electrical output that reflects this condition, it is properly termed a transducer.

There are many types of transducers in use today. Some of the more familiar ones include: microphones, which convert sound into electrical energy; strain gages, which convert stress into electrical energy; accelerometers, which convert acceleration into electrical energy. It would be impossible to list all of the transducers and their application. New types of transducers are being created every day to meet new applications. Some controlled variables with appropriate detecting and measuring elements are shown in the following table.

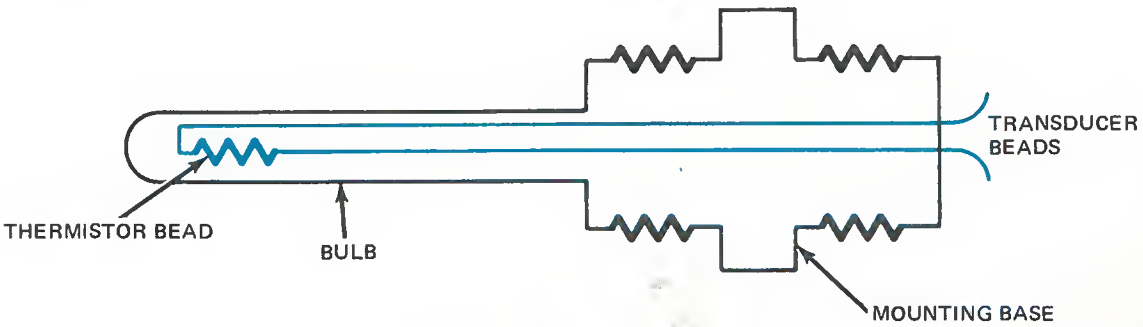


Fig. 2-1 A Thermal Transducer

Process Variable	Sensing Device	Measuring Elements
Temperature	Thermocouple Thermistor Thermometer Bulb	Galvanometer or Bridge Bridge Network Bourdon Tube
Rate of Flow	Turbine Generator in Flow Path Magnetic Flowmeter Orifice Plate or Venturi Tube	Pulse Counter Galvanometer or Bridge Network Mercury Manometer and Float Diaphragm Using Balance, etc.
Strain, Torque, Tension and Force	Resistance Strain Gage	Bridge Network
Velocity	Fly-Ball Governor Tachometer Generator	Linkage and Points Electrical Deflecting Instrument or Network
Displacement or Position	Linear Potentiometer Rotary Potentiometer Capacitors Synchronous Transmitter Photo-electric Cell Flapper and Nozzle	Bridge Network or Electronic Network Electronic Network Synchronous Receiver Electronic Circuit
Pressure	Bourdon Tube Diaphragm Bellows	Motion-Potentiometers Linkage and Pointer

Fig. 2-2 Table of Controlled Variables

Process Variable	Sensing Device	Measuring Elements
Level	Floats Electrodes Capacity Probes Photo-electric X-Ray Radioactive	Linkages and Pointer Electronic Networks Electronic Networks Electronic Networks Sensitive Materials Geiger-Mueller-Tube
Thickness	X-Ray Ultrasonic Radioactive	X-Ray Sensitive Material Electronic Oscillators and Bridge Circuit Geiger-Mueller-Tube
Proximity	Magnetic Pickups Photo Detectors	Electronic Circuit Photovoltaic, Photoconductive and Photo-emissive Devices
Humidity	Hair Hygrometer	Thermometers and Electrical Bridge Electrical Circuit and/or Bridge
Density Conductivity and PH	Various Sensors	Electrical Bridges, etc.

Fig. 2-2 Table of Controlled Variables (Cont'd)

Many industrial processes require transducers to detect the displacement or position of some moving component, the amount of movement, and the direction. These sensors act by converting the linear or angular motion into an electrical signal that reflects the displacement or position.

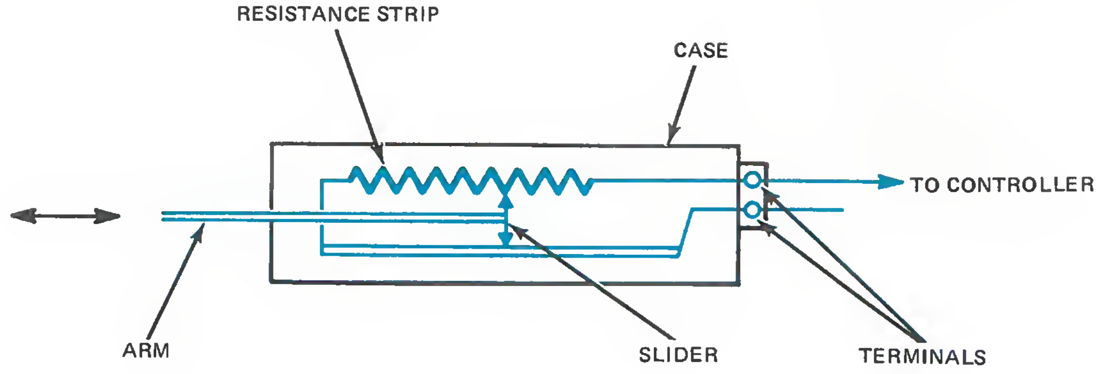


Fig. 2-3 Linear-Motion Potentiometer

The linear-motion potentiometer shown in figure 2-3 converts linear motion into changes in resistance. The slider, connected to the moving component, moves over the resistance element. The movement of the slider varies the resistance between the output terminals. When the moving component moves to the right, so does the slider. As a result the resistance between the output terminals is decreased. When the component moves to the left, so does the slider. As a result the resistance between the output terminals is increased. Thus, the resistance change of the potentiometer reflects the amount of linear movement and the direction of the movement.

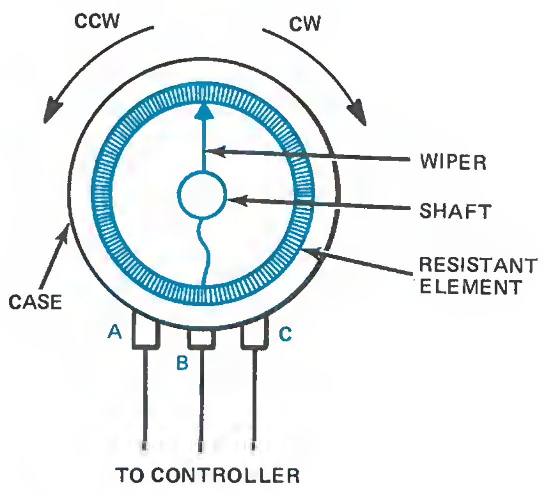


Fig. 2-4 Angular-Motion Potentiometer

The angular-motion potentiometer shown in figure 2-4 converts angular motion into changes in resistance. The angular rotation of the shaft, connected to the rotating component, varies the resistance between the output terminals. When the shaft is rotated in the clockwise direction, the resistance between terminals A and C increases, and the resistance between terminals B and C decreases. When the shaft is rotated in the counterclockwise direction, the resistance between terminals A and C decreases and the resistance between terminals B and C increases. Thus, the resistance change in the potentiometer reflects the amount of angular movement and the direction of rotation. Note that this sensor is limited to approximately 300° of rotation.

The tachometer, figure 2-5, converts angular motion into a voltage that reflects the speed of rotation. It consists of a small DC generator whose field is produced by a permanent magnet. The angular rotation of the armature coupled to the rotating component in a magnetic field produces an output voltage that is directly proportional to the speed at which it is rotated. The tachometer may also be of the AC type, in which case the frequency of the voltage output is a function of the speed of rotation.

The bonded wire strain gage shown in figure 2-6 can be used to sense pressure, compression, tension and torsion. The resistance of a wire depends upon its length, cross-sectional area, and temperature. If the temperature is held constant, the resistance of the wire is directly proportional to its length, and inversely proportional to its cross-sectional area. The strain gage is a fine wire filament about 0.001 in. in diameter made from an alloy of copper and nickel which has a relatively high elasticity. When a strain, caused by compression or tension, stretches the wire of the strain gage, the cross-sectional area is reduced and the overall length is increased. Both of these factors cause an increase in the electrical resistance of the strain gage.

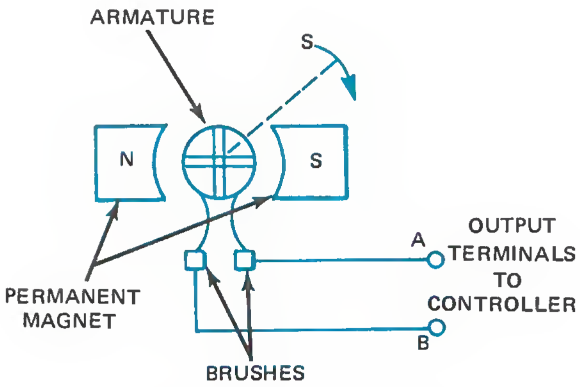


Fig. 2-5 DC Tachometer

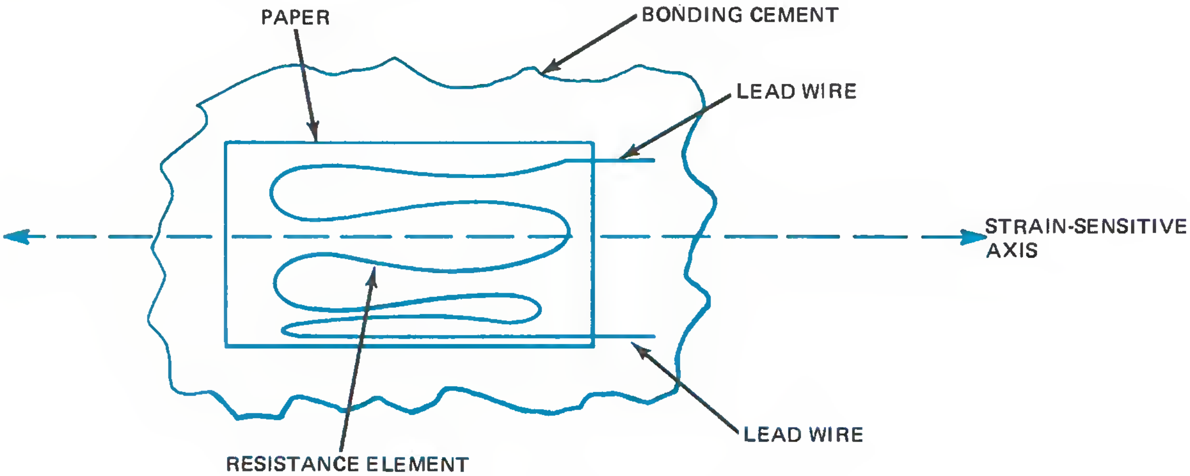


Fig. 2-6 The Bonded Strain Gage

The bourdon tube, figure 2-7, can be used to measure the pressure of a fluid. It is a tube of elliptical cross section made of thin, springy metal formed into an incomplete spiral. One end of the tube is fixed and provides an inlet for the fluid. The other end is sealed and is free to move. As the pressure inside the tube is increased, the tube tends to straighten. As the pressure is reduced, the tube tends to return to its original curved

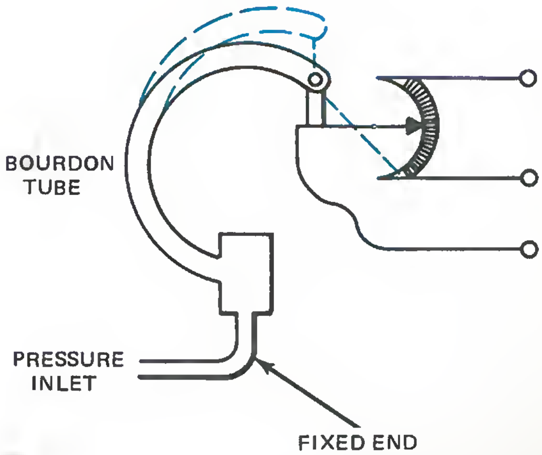
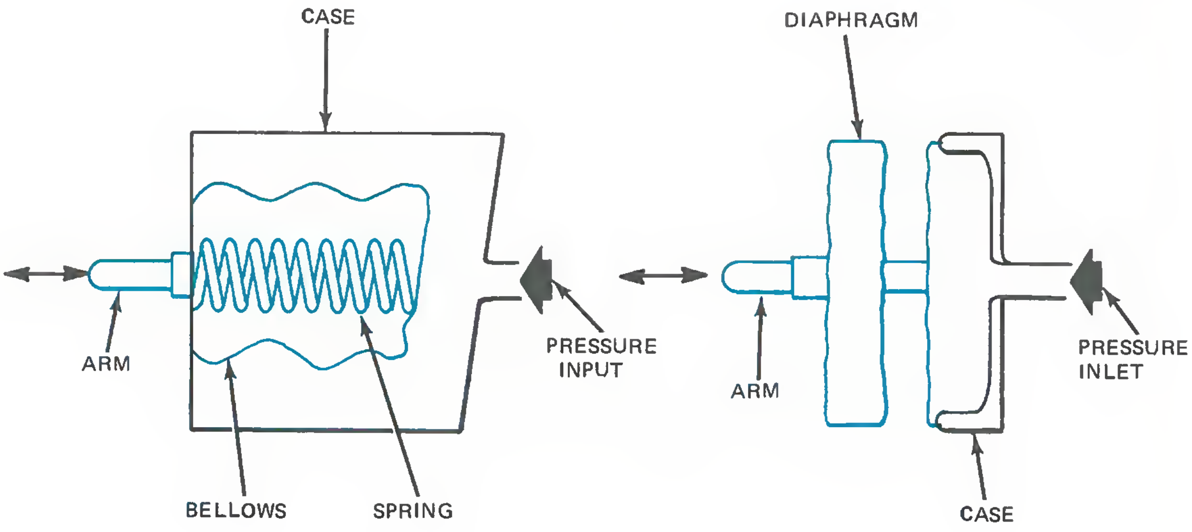


Fig. 2-7 Pressure Measurement Using Bourdon Tube and Angular-Motion Potentiometer



(A) BELLOWS TYPE

(B) DIAPHRAGM TYPE

Fig. 2-8 Pressure Transducer

form. The movement of the free end is proportional to pressure changes and produces an output signal that reflects these changes. The free end of the tube can be linked through a mechanical coupling to a pointer over a scale calibrated in units of pressure. The assembly is then called a pressure gage. When a high range of pressure is to be measured, a flat-spiral bourdon tube is used.

Bellow-type or diaphragm elements are used where the pressures involved are low. These transducers are shown in figure 2-8.

To measure the rate of flow of fluid in a closed pipe, energy is extracted from the moving fluid itself. In mechanical flowmeters, the flow of fluid causes motion within the measuring unit. This is transmitted via gearing to a pointer. In the differential-pressure type of flowmeter, a restriction, in the form of an orifice plate or venturi, is placed in the pipeline to give an increase in velocity which is accompanied by a decrease in pressure. This decrease is a measure of the rate of flow. A flowmeter having no moving parts and offering no obstruction to the flowing liquid uses the principle that an emf is induced in a conductor moving in a magnetic field. The magnetic flowmeter is shown in figure 2-9. The moving fluid is the conductor and its flow provides the required movement. An emf is detected by two electrodes embedded in, but insulated from, the wall of the tube through which the liquid flows. The required magnetic field is produced by an electromagnet. If the field strength is kept constant, the emf induced is a direct measure of the rate of flow.

There are many processes in which it is necessary to maintain a given level of liquid in a vessel. The capacitive liquid-level transducer is shown in figure 2-10. The capacitance of a capacitor with parallel plates is directly proportional to the dielectric constant and the area of plates, and inversely proportional to the distance between the plates. If the area of the plates and the distance between the plates are kept constant, the capacitance of the capacitor will vary with the value of the dielectric constant. The capacitive liquid-level

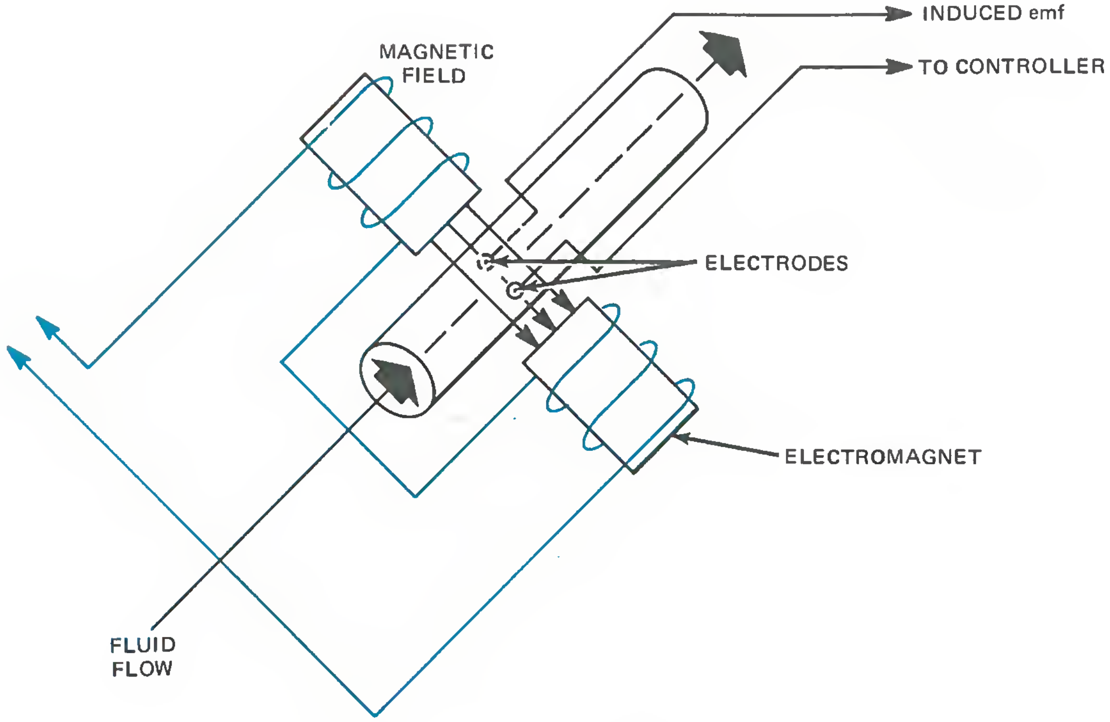


Fig. 2-9 Electromagnetic Flowmeter

transducer consists of an insulated metal electrode mounted near and parallel to the metal wall of the tank. The wall of the tank and the electrode form the plates of the capacitor and the liquid acts as the dielectric. The capacitance of the capacitor depends on the height of the dielectric (liquid) between the plates. The greater the height, the larger the capacitance and the less the height, the smaller the capacitance. The capacitance is directly proportional to the level of the liquid in the vessel.

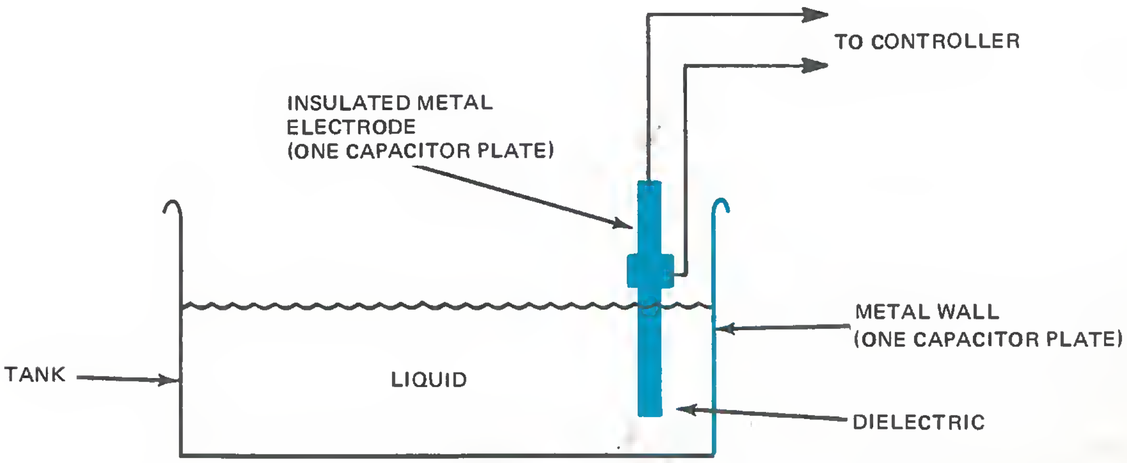


Fig. 2-10 Capacitive Liquid-Level Transducer

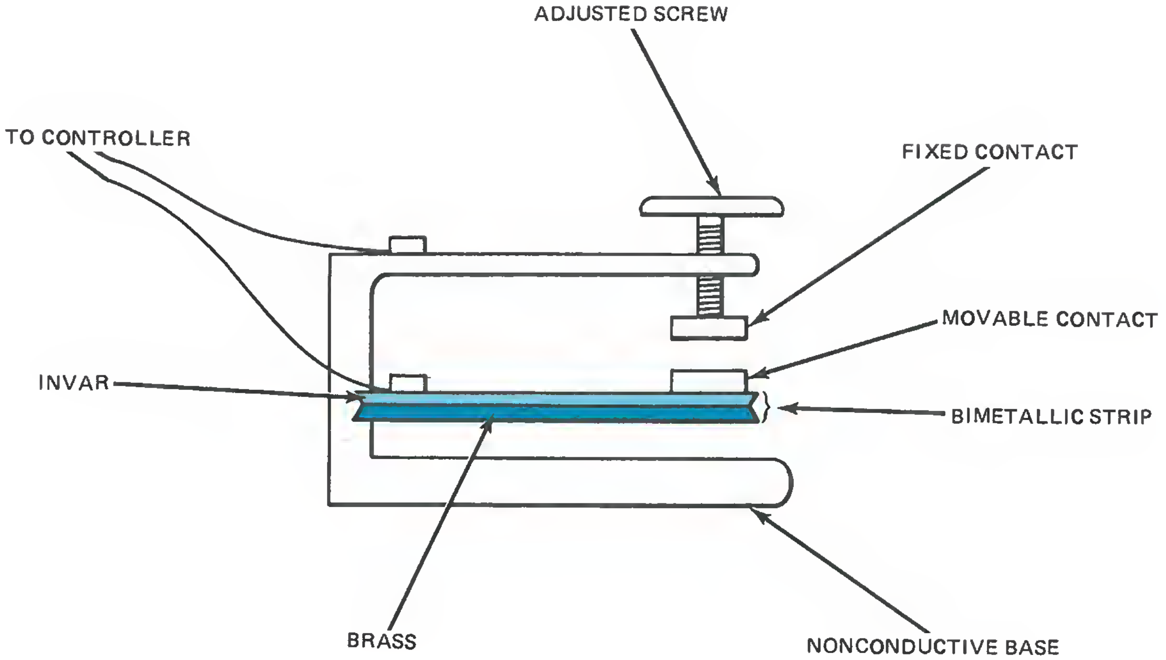


Fig. 2-11 Bimetallic Thermostat

The bimetallic thermostat shown in figure 2-11 is a thermal transducer used to sense changes in temperature. The bimetallic strip consists of two dissimilar metals welded together, each with a different temperature *expansion* constant. The strip is made of brass, which has a relatively large rate of expansion, and an alloy of nickel and iron (called invar), which has a relatively small rate of expansion. When heated, the brass expands at a greater rate than the invar. As a result of this uneven rate of expansion, the free end of the strip bends upward, closing the contacts. When cooled, the strip returns to its normal position, opening the contacts. The temperature at which the contact points open or close can be controlled by means of an adjusting screw, which brings the fixed contact nearer or farther away from the movable contact.

Phototubes, photomultipliers, photovoltaic cells, photoconductive cells and phototransistors are light-sensing transducers that convert light energy into electrical energy. X-ray and radioactive sensors can be used for detecting the level of liquids in closed tanks, or the thickness of a sheet of material. Magnetic pickups are used to detect proximity and in counting processes. Humidity sensors, such as the hair hygrometer, are used to detect moisture content.

The transducers contained in this experiment are but a few of the many devices used as sensors in industry today. The objective of this experiment reflects the heat of the automatic control system and is of sufficient importance to be restated. In order to successfully control a machine or a process, automatically, the state, condition or value of the variable to be controlled must be detected and measured. The transducer is a device used in automatic control systems to sense a state, condition or value of the process variable and to transform a portion of its energy into an output signal of some type.

MATERIALS

1 Stepping motor, 28 volt
1 Angular motion-potentiometer, 20 kΩ
1 Adapter coupling
1 Scale and indicator assembly
1 Wheatstone bridge
1 VOM or FEM
2 DC power supplies 0-40V
1 Resistor, 1 kΩ, 1/2W
2 Resistor, 10 kΩ, 1/2W
1 Switch, SPST

PROCEDURE

1. Assemble the motor, potentiometer, and indicator assembly as shown in figure 2-12.

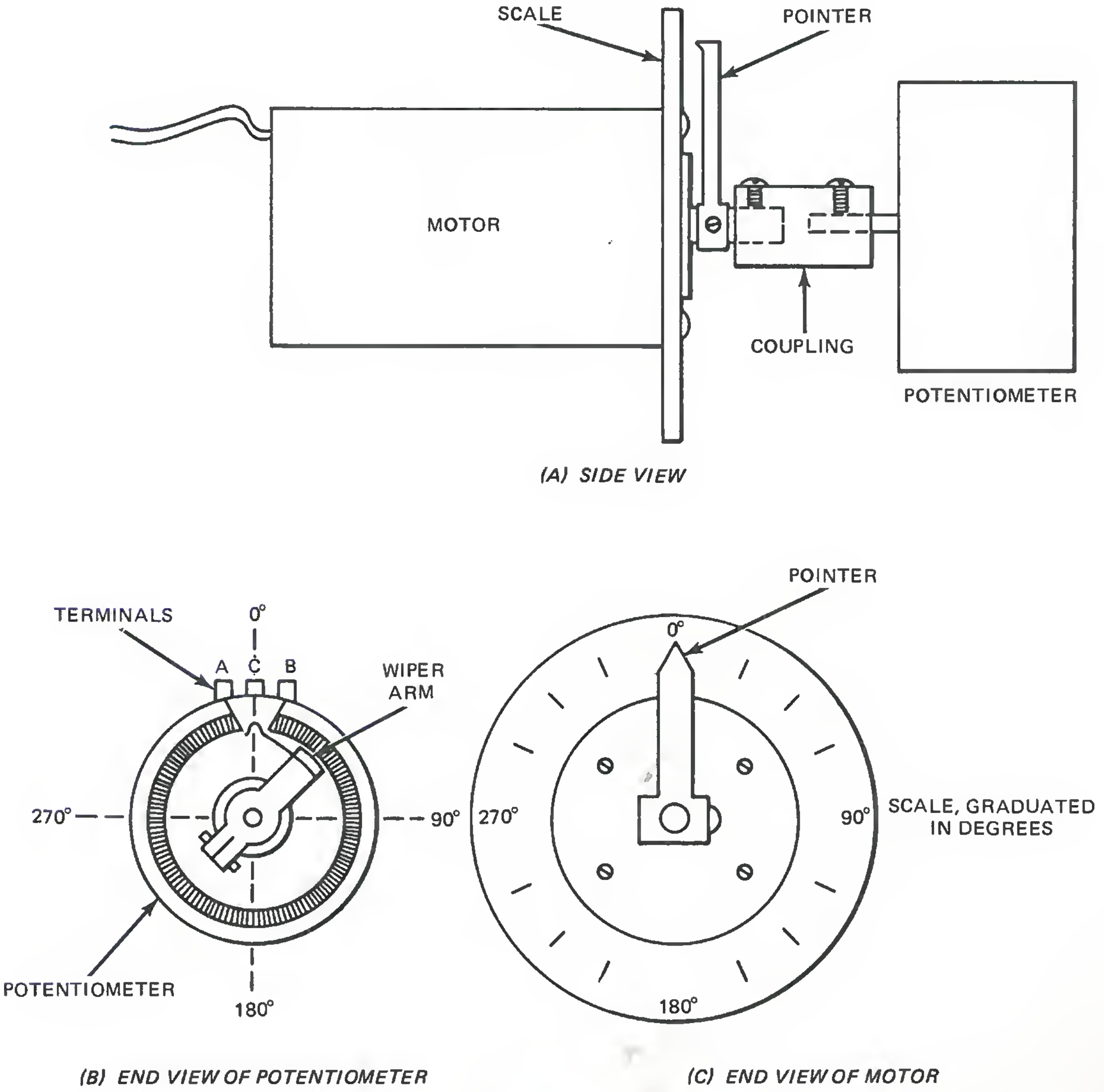
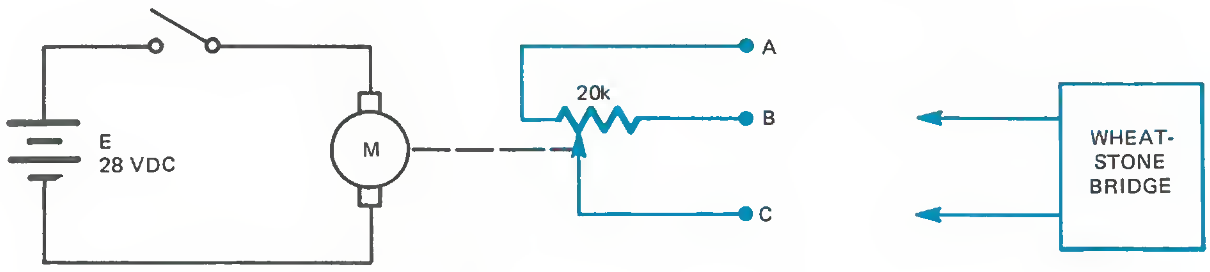
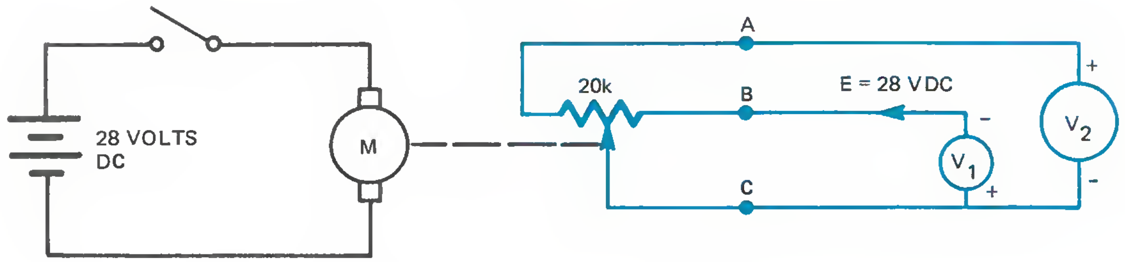


Fig. 2-12 The Mechanical Setup

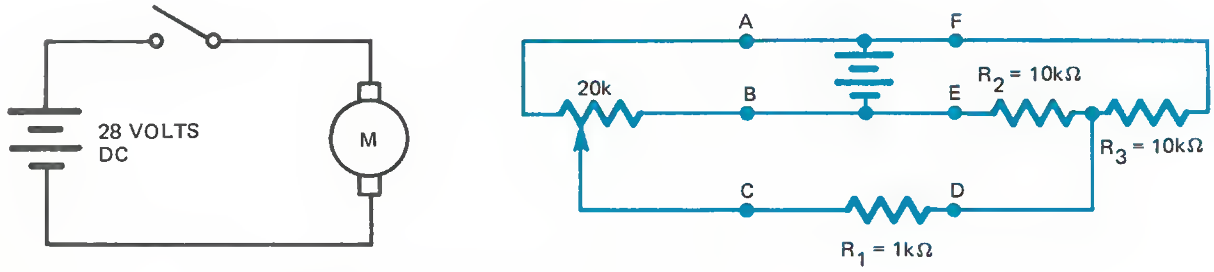
2. Construct the experimental circuit as shown in figure 2-13A.



(A) ANGULAR POSITION WITH RESISTANCE OUTPUT



(B) ANGULAR POSITION WITH VOLTAGE OUTPUT



(C) ANGULAR POSITION WITH ERROR DETECTION

Fig. 2-13 The Experimental Setup

3. Set the pointer of the indicator to zero degrees. Loosen the set screw securing the potentiometer wiper arm contact to a midpoint position between the ends of the resistance element. Secure the potentiometer shaft to the motor by tightening the set screw.

4. With a Wheatstone bridge, measure the resistance between terminals A to B, A to C, and B to C. Record these in the Data Table, figure 2-14A.

Position in Degrees	Resistance		
	A to B	A to C	B to C
0°			

Steps 4-6 Results

Fig. 2-14A The Data Table

5. Step the motor one step by closing the switch. After the motor has stepped, turn the switch off.

6. Measure the resistance, with the Wheatstone bridge, between terminals A to B, A to C, and B to C. Record these data and the angular position indicated by the pointer.

7. Repeat steps 5 and 6 until one complete revolution of the motor shaft has been attained.

8. Construct the experimental circuit as shown in figure 2-13B.

9. Repeat steps 3 through 7 for the voltage, measured with a DC voltmeter, between terminals A to B, A to C, and B to C. Record these data in the Data Table, figure 2-14B.

Position in Degrees	Voltage		
	A to B	A to C	B to C
0°			

Step 9 Results

Fig. 2-14B The Data Table

10. Construct the experimental circuit as shown in figure 2-13C.

11. Repeat steps 3 through 7 for the voltage between terminals B to C, E to D and D to C. Record these data in the Data Table, figure 2-14C.

ANALYSIS GUIDE. In the analysis of these data, a discussion concerning the use of the angular motion potentiometer as a position or displacement transducer should be presented. Plot the voltage, V_{DC}, versus angular position in degrees for the data recorded in the data table.

Position in Degrees	Voltage		
	V_{BC}	V_{ED}	V_{DC}
0°			

Step 11 Results

Fig. 2-14C The Data Table

PROBLEMS

1. Describe, in your own terms, the function of a transducer.
2. Why is it necessary to use a sensor in a closed-loop control system?
3. Is a sensor necessary in an open-loop control system? Why?
4. What is an error signal? How is it generated?
5. Name and discuss the operation of two transducers not included in the discussion of this experiment.

experiment 3 CONTROLLERS

INTRODUCTION. The part of a control system which compares the measured value of the controlled variable with the desired value and operates to correct or limit deviation from the desired value is called a *controller*. In this experiment, the basic principles and modes of operation of a controller will be investigated.

DISCUSSION. To understand the function of a controller, the role it plays in an automatic control system should be examined. The sensing device or transducer senses the condition, state or value of the variable to be controlled and produces an output signal that reflects this condition, state or value. The output of the sensor is accepted by the controller, which measures it and compares it with a reference signal (set-point) which corresponds to the desired condition, state or value of the process variable. Any deviation between the two signals (error) is detected and an output signal is generated to the final control element (actuator) which acts to bring the condition, state, or value of the process variable to that indicated by the set-point, thus eliminating the error or deviation. Production of the counteraction is called the characterization of the controller output signal and the method employed is called the mode of control.

There are four different modes of control: On-Off, Proportional, Reset and Rate. Each has its own characteristics and purpose. The controller may use either a single mode of operation or a combination of the different modes.

In **On-Off Control**, sometimes called two-position control, the controller operates the actuator at only two positions, which are generally located at a minimum and maximum. If the controlled variable is greater than the set-point, the controller causes the actuator to be at its minimum position, usually Off. If the controlled variable is less than the set-point, the controller causes the actuator to be at its maximum position, usually On. This mode of control is shown in figure 3-1.

When the level of the liquid in the vessel rises above a predetermined level (set-point), the float causes the switch contacts to open. Opening of the switch contacts de-energizes the electrically-operated solenoid valve and the liquid inflow is cut off. When the level of the liquid in the vessel drops below the predetermined level, the float causes the switch contacts to close. Closing the switch contacts energizes the electrically-operated solenoid valve and the liquid inflow is turned on.

The level of the liquid in the vessel may be changed by adjusting the set-point, higher or lower as desired. The time interval of the "On" to "Off" time is varied in accordance with the load demand. In the On-Off Controller, there is no happy medium that the controller uses in correcting the controlled variable toward the desired condition. The actuator is either full On or full Off.

In **Proportional Control**, there is a continuous linear relationship between the value of the deviation and the actuator manipulation. The ratio of the percentage of full scale signal of the transducer to the percentage of full-scale output from the controller is called

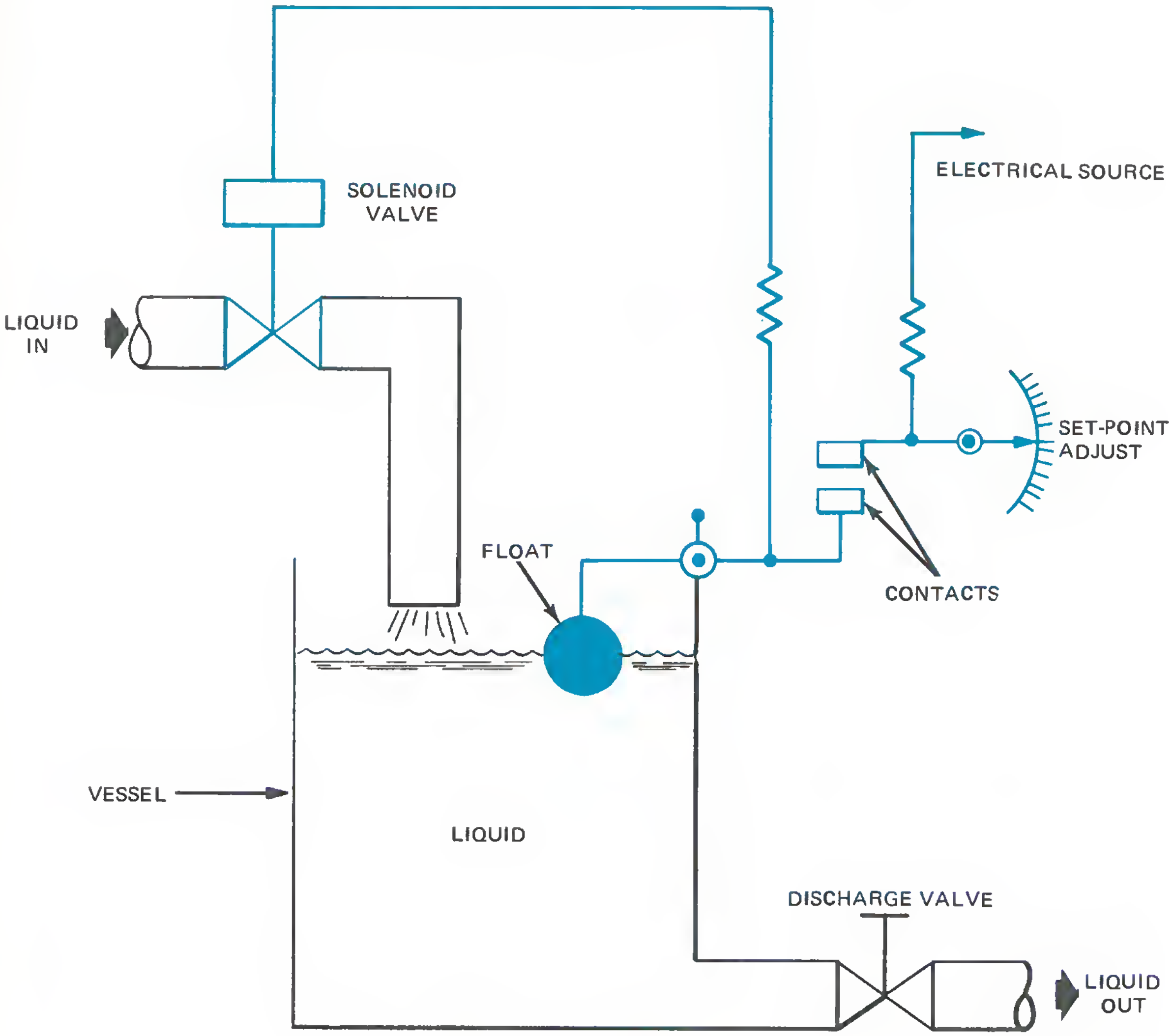


Fig. 3-1 Two-Position Control

the *proportional band.* The smaller the proportional band, the more precise the control over the process. In some controllers the proportional band can be manually set as desired. The purpose of the proportional band is to permit a maximum actuator movement with a large process variable. Processes controlled only by proportional action will always result in a small difference between the controller set-point and the controlled variable. This difference is called offset. Reducing the proportional band can reduce the offset, but if reduced too far, the system will become unstable and hunt. In other words, it will have continuous actuator movement.

Hunting or instability is usually an undesirable condition, but in order to make a proportional controller as fast-acting as possible in a system, it is common practice to decrease the proportional band (increasing the *gain* or sensitivity) until this condition is experienced and then increase the band until the hunting stops.

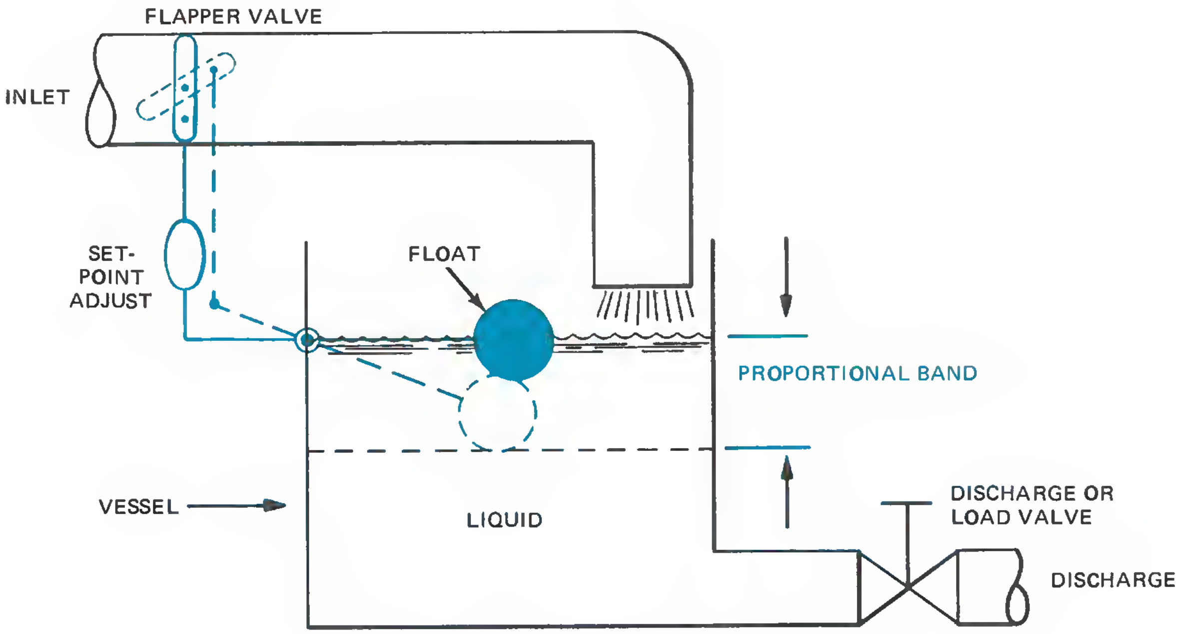


Fig. 3-2 A Proportional Control

The proportional mode of control is illustrated in figure 3-2. In this system, the float lever is connected through a turnbuckle to a flapper valve. The turnbuckle functions as an adjustable set-point device. When the level of the liquid in the vessel rises above the predetermined set-point, the float causes the flapper valve to close a proportionate amount. This reduces the inflow to the vessel and tends to prevent the level from rising. When the level of the liquid in the vessel falls below the predetermined set-point, the float causes the flapper valve to open a proportionate amount. This increases the inflow to the vessel. The range of water level necessary to move the inlet valve between the two extreme positions is the proportional band. At all other levels within the proportional band the inflow valve is adjusted in proportion to the amount that the level is away from the set-point. In proportional control, the controlled variable cannot be held constant at all loads without set-point adjustment. However, the proportional band can be reduced until the variation in the controlled variable is tolerable. The proportional band can be reduced by moving the float closer to the fulcrum of its lever arm.

In Reset Control, sometimes called integral control, the output of the controller is varied by an amount that is related to the difference between the set-point and the controlled variable, and the "time" that this difference or error exists. Reset control is normally used with a proportional control and such a controller could be called a proportional-plus-reset controller.

Integral, reset, control is illustrated in figure 3-3. Two disks coupled by a friction drive roller operate a screw control valve through a set of gears. One of the disks is driven at constant speed by an electric motor. The position of the friction drive roller is controlled by the float arm. When no error exists, the drive roller is at a neutral position, zero speed. When the level of the liquid in the vessel falls below the set-point, the drive roller

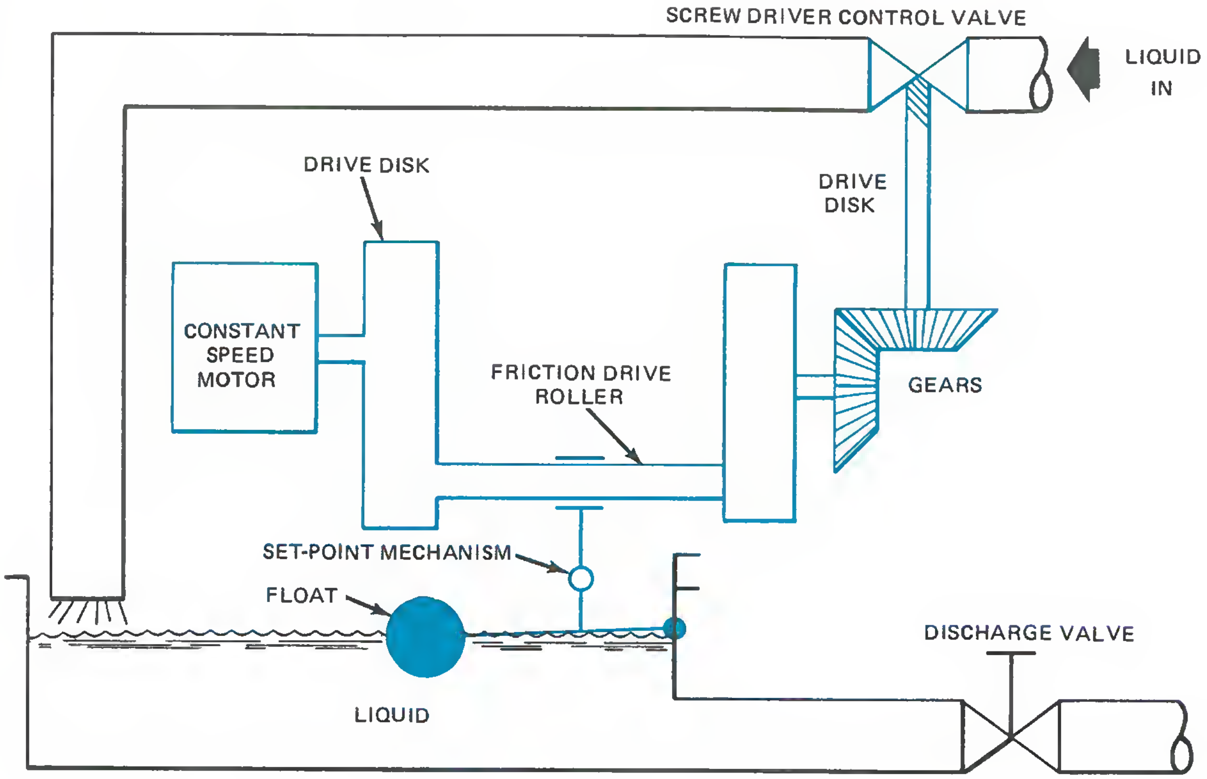


Fig. 3-3 An Integral Control

moves below the neutral point, and the valve is moved outward at a rate that is proportional to the deviation. When the level rises above the set-point, the drive roller moves above the neutral point, and the valve is moved inward at a rate that is proportional to the deviation. When the deviation is zero, the valve is stationary.

The reset rate is the number of times per minute that the proportional part of the response is duplicated. Reset rate is therefore called "repeats per minute" and is the inverse of integral time. Reset response, when added to proportional control, acts to eliminate the offset produced by a load change. The controller output continues to drive the actuator as long as the measured variable is not at the set-point. The rate of control by the actuator changes with the amount of deviation from the set-point.

In a *proportional-plus-reset* control, when an error between the set-point and the controlled variable exists, the change in the output of the controller produced by the proportional effect and the change produced by the reset effect commence immediately to cause the actuator to reduce the amount of error. The rate of reduction of error decreases with "time" because of the corrective action of the actuator. As the error becomes less and less, the rate of output signal change becomes very small until finally the output of the controller is constant and the error between the set-point and the controlled variable is zero. The controller output signal change with proportional-plus-reset control is an exponential; therefore, the actuator drives the controlled variable toward the set-point in a smooth and continuous manner. The advantage of adding reset to proportional control is that the controlled

variable is brought back to the set-point even though a new actuator position is required. The controlled variable can therefore be maintained at the set-point throughout the load range of the equipment.

In Rate-Action Control, sometimes called derivative control, the output of the controller is proportional to the rate of change of the deviation or error. Rate control is used together with other types of control to return the controlled variable to the set-point more quickly by anticipating or accelerating the control action required.

As a quick review, there are four general types of control: On-Off control, in which the controller operates the actuator at either maximum capacity or minimum capacity; Proportional Control, in which the controller operates the actuator in a continuously linear relationship that is proportional to the error signal; Reset Control, in which the controller operates the actuator in some manner that is related to the deviation between the set-point and the controlled variable and the time during which the deviation exists, and Rate Control, in which the controller operates the actuator in some manner that is related to the rate at which error signal changes.

MATERIALS

- 1 Thermostat, type 923A or equivalent
- 1 Dual pressure control, type 012-1505 or equivalent
- 1 Heater element, 100-watt light bulb
- 1 Switch, 115-volt, 10-amp, SPST
- 1 Relay, 24V coil with SPDT contacts
- 1 Air supply 0-15 psi regulated contact arrangement
- 1 Pressure gage, 0-30 psi
- 1 Hand valve
- 1 Switch, SPST
- 1 Cardboard box, approximately 10 x 10 x 10 in.
- 1 DC power supply, 0-40V
- 1 Fan, 115-volt, 60-Hertz
- Miscellaneous couplings

PROCEDURE

1. Construct the experimental setup shown in figure 3-4.
2. Close the manual hand valve and adjust the regulated air pressure to 11 psi.
3. Adjust the low pressure range screw to a "cut-in" setting of 10 psi.
4. Adjust the low pressure differential to a "differential" setting of 5 psi.
5. Adjust the thermostat control to 90°F.
6. Measure and record the temperature inside the box in the Data Table, figure 3-5.

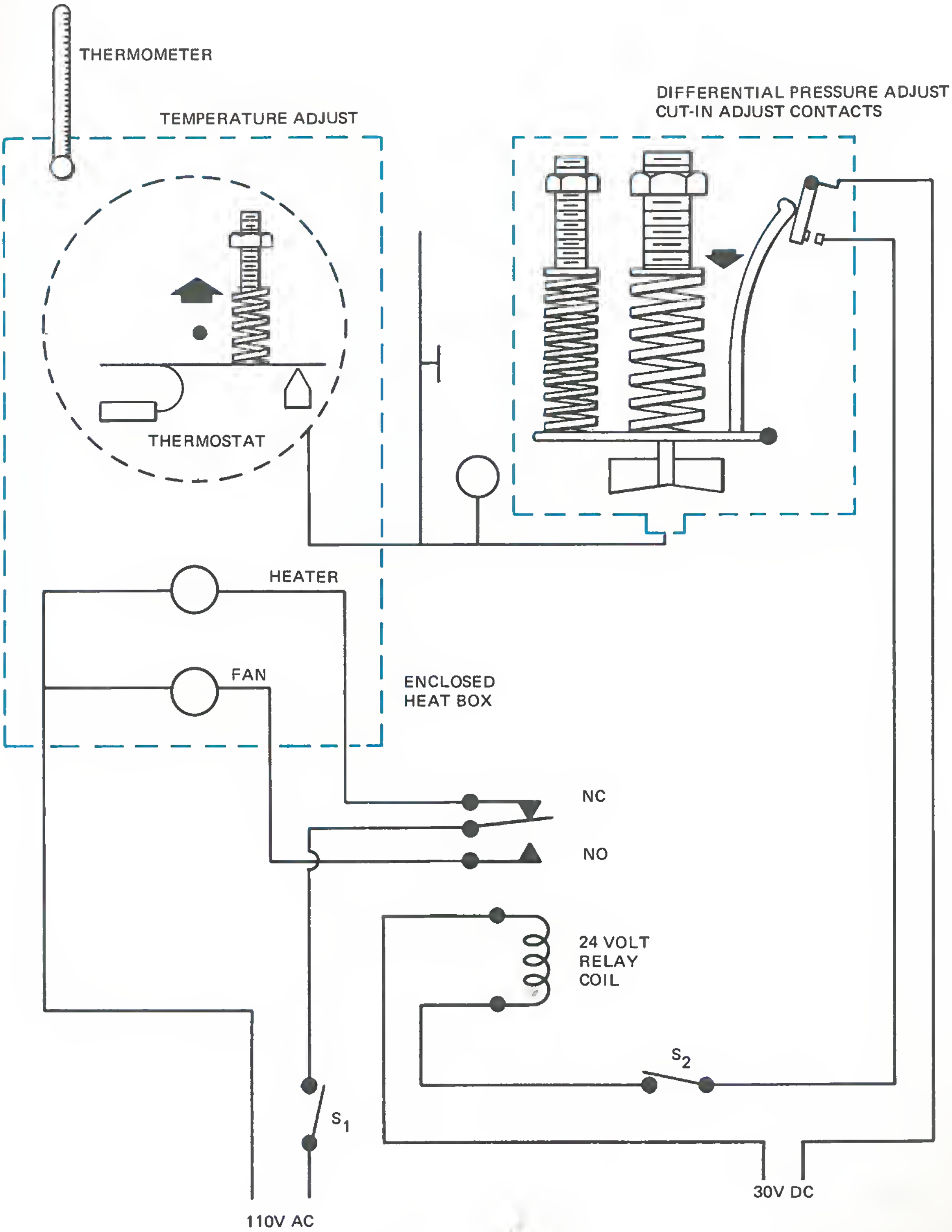


Fig. 3-4 The Test Setup

7. With your hand, hold the flapper against the nozzle opening and carefully open the hand valve until the contacts in the pressure control unit close. Release the flapper and record the pressure in the Data Table.
8. Turn S_1 and S_2 on.
9. For every 1°F temperature change, record the pressure, temperature and the time in the Data Table.

90°F Setting		
Temp. (°F)	Pressure (psi)	Time
79		
80		
81		
82		
83		
84		
85		
86		
87		
88		
89		
90		
91		
92		
93		
92		
91		
90		
89		
88		

90°F Setting		
Temp. (°F)	Pressure (psi)	Time
89		
90		
91		
92		
93		
92		
91		
90		
89		
88		
89		
90		
91		
92		
93		
92		
91		
90		
89		
88		

Fig. 3-5 The Data Table 90°F

10. Adjust the fan position so that the time On to time Off of the heater element is equal and repeat step 9 for 3 cycles of the temperature variation (maximum to minimum, etc.).
11. Repeat steps 9 and 10 for a thermostat setting of 80°F. Record these data in the Data Table, figure 3-6.

80°F Setting		
Temp. (°F)	Pressure	Time
79		
80		
81		
80		
79		
80		
81		
80		
79		
80		
81		
80		
79		

Fig. 3-6 The Data Table 80°F

ANALYSIS GUIDE. Explain the On-Off mode of operation in connection with a heating system. Explain the variations observed and the differential temperature and relate these terms to your data. Prepare a graph of Temperature versus Time for the 80° and 90° thermostat settings as recorded in your data.

PROBLEMS

1. What physical quantity activates the thermostat?
2. Explain in detail how a change in temperature operates the thermostat.
3. What is the set-point device?
4. What is the actuator?

experiment **4** ERROR GENERATORS

INTRODUCTION. In an automatic controller, the device or stage that compares the transducer output with the set-point and generates an error signal is called the comparator or error generator. In this experiment, methods of error generation will be examined.

DISCUSSION. The error generator device or stage of a controller compares the transducer output with the set-point output to determine any deviation between the two. If a deviation exists, an error signal is developed that reflects the amplitude and phase of the deviation. The error signal is then amplified to a level necessary to drive the actuator.

In an electronic controller, the error may be generated by a ratio network, a bridge network, a summing amplifier, a differential amplifier or a synchro arrangement. A DC ratio network used as an error generator is shown in figure 4-1. In analyzing how the ratio detector operates, assume that $R_1 = R_2 = R_3 = R_4 = R_5 = 1\ k\Omega$, and the set-point input voltage is 10 volts DC. When the controlled variable is at the desired operating value, the output of the transducer is 10 volts DC. The output of the error generator stage may be calculated by thevenizing the circuit. Resistor R_5 will be used as the load. The thevenized equivalent circuit is shown in figure 4-2. The symbol (+) indicates that a point is assumed to be of positive polarity.

Suppose that the transducer input decreases to 5 volts DC. The error voltage would be determined by

$$V_{BA} = \frac{E_{th}\ R_5}{R_{th} + R_5}$$

R_{th} remains the same value, but E_{th} has changed to a new value of

$$E_{th} = \frac{E_{SP} R_2}{R_1 + R} - \frac{E_{TR} R_4}{R_3 + R_4}$$

$$E_{th} = \frac{10(1k)}{1k + 1k} - \frac{5\,(1k)}{1k + 1k}$$

$$E_{th} = 5 - 2\ 1/2 = 2\ 1/2 \text{ volts}$$

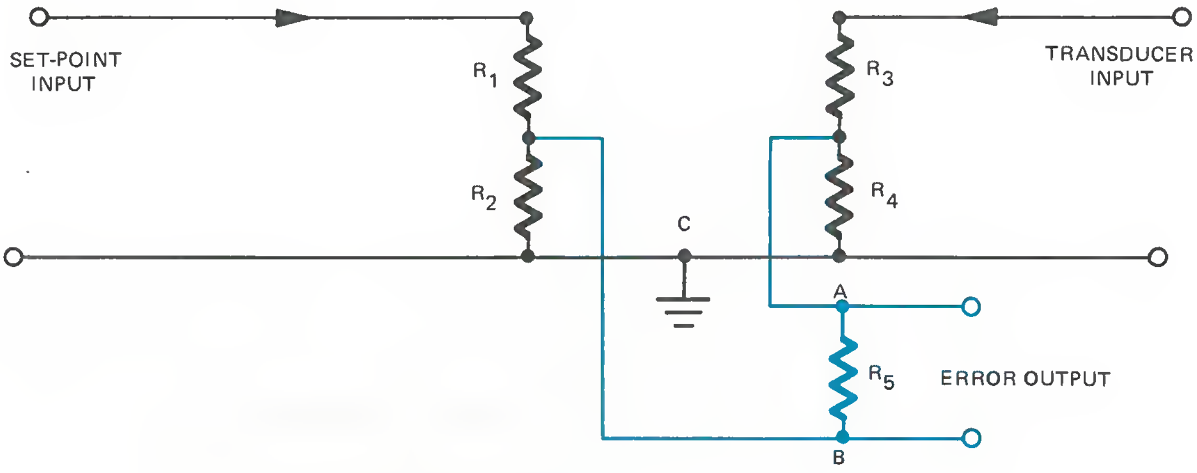


Fig. 4-1 Ratio Network For Error Generation

and V_{BA}, the output error signal, is

$$V_{BA} = \frac{2\ 1/2\ (1k)}{1k + 1k} = 1\ 1/4 \text{ volts}$$

with point B positive with respect to point A.

Now suppose that the transducer input increases to 15 volts. The error voltage would be determined by solving the circuit 4-2A for the thevenized resistance:

$$R_{th} = \frac{R_1 R_2}{R_1 + R_2} + \frac{R_3 R_4}{R_3 + R_4} -$$

$$R_{th} = \frac{1k\ (1k)}{1k + 1k} + \frac{1k\ (1k)}{1k + 1k}$$

$$R_{th} = 1 \text{ kilohm}$$

Then solving the circuit in 4-2B for the thevenized voltage,

$$E_{th} = V_{BC} - V_{AC}$$

$$E_{th} = \frac{E_{sp} R_2}{R_1 + R_2} - \frac{E_{tr} R_4}{R_3 + R_4}$$

$$E_{th} = \frac{10(1k)}{1k + 1k} - \frac{10\ (1k)}{1k + 1k}$$

$$E_{th} = 0$$

Finally solving the circuit in 4-2C for the error voltage, V_{BA}, we have

$$V_{BA} = \frac{E_{th}\ R_5}{R_{th} + R_5}$$

$$V_{BA} = \frac{0\ 1k}{1k + 1k} = 0$$

$$V_{BA} = \frac{E_{th}\ R_5}{R_{th} + R_5}$$

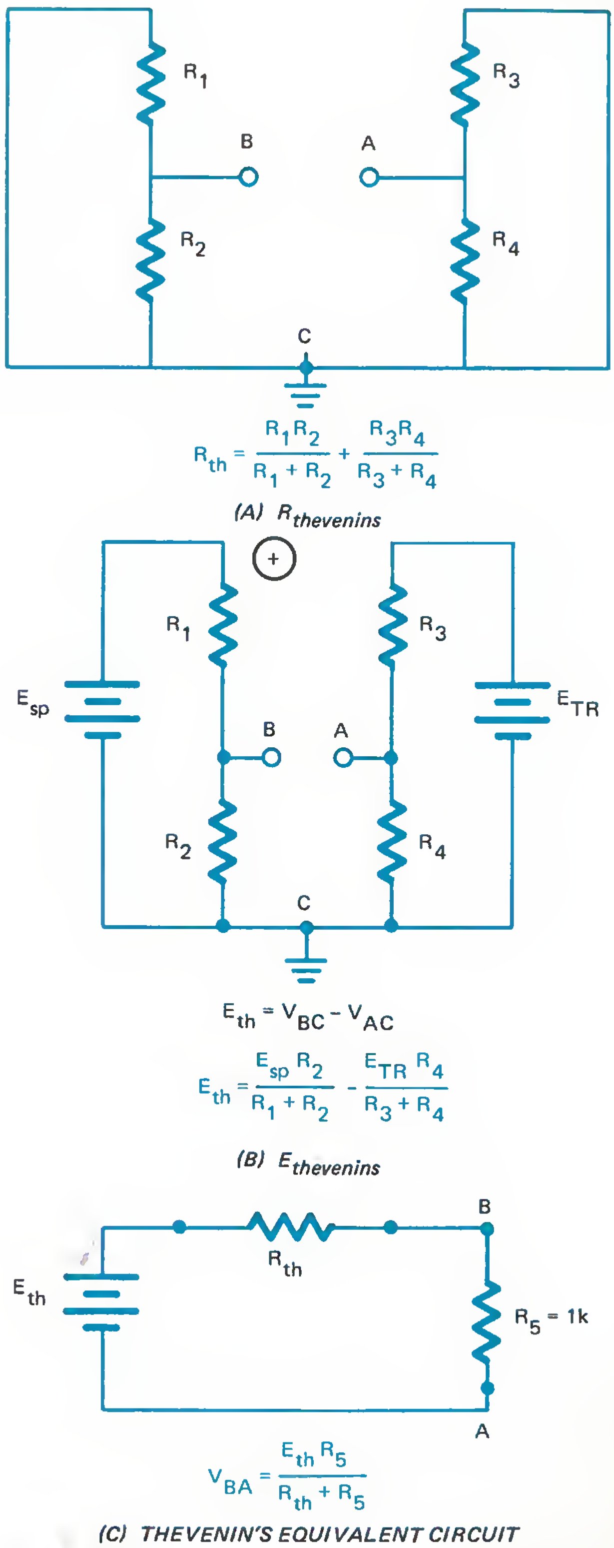
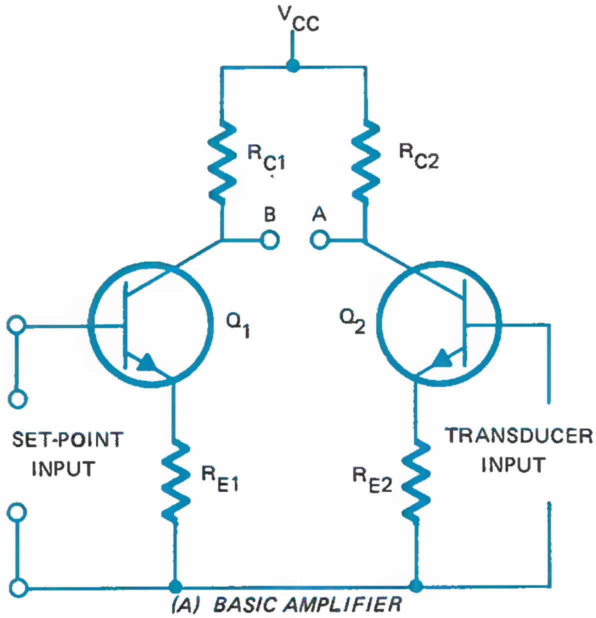


Fig. 4-2 Thevenin's Equivalent Of Ratio Detector



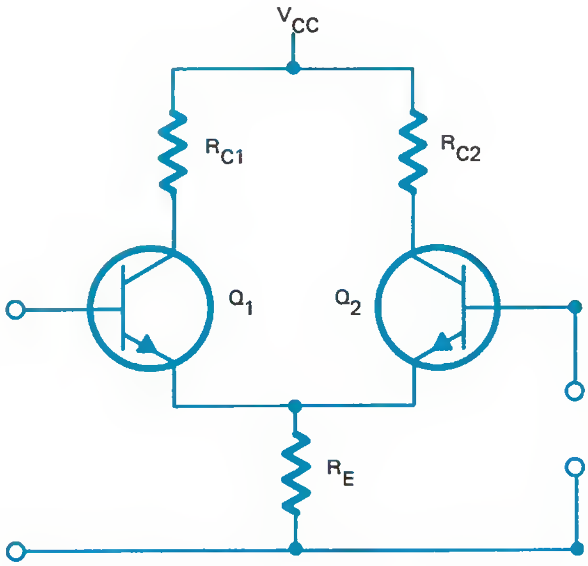


Fig. 4-3 The Differential Amplifier

R_{th} remains the same value, but E_{th} has changed to a new value of

$$E_{th} = \frac{E_{sp} R_2}{R_1 + R_2} - \frac{E_{th} R_4}{R_3 + R_4}$$

$$E_{th} = \frac{10\,(1k)}{1k + 1k} - \frac{15\,(1k)}{1k + 1k}$$

$$E_{th} = 5 - 7\text{-}1/2 \text{ volts} = -2\text{-}1/2 \text{ volts}$$

and V_{BA}, the output error signal, is

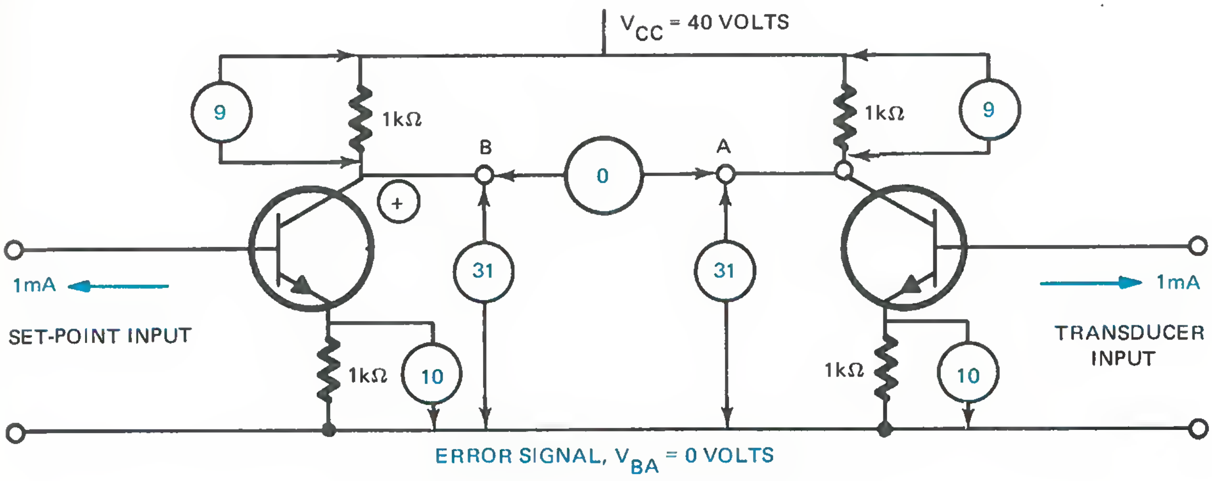
$$V_{BA} = \frac{-2\text{-}1/2\,(1k)}{1k + 1k} = -1\text{-}1/4 \text{ volts.}$$

Thus, the output error signal reflects the amplitude of the deviation between the transducer output and the set-point, as well as the direction of deviation.

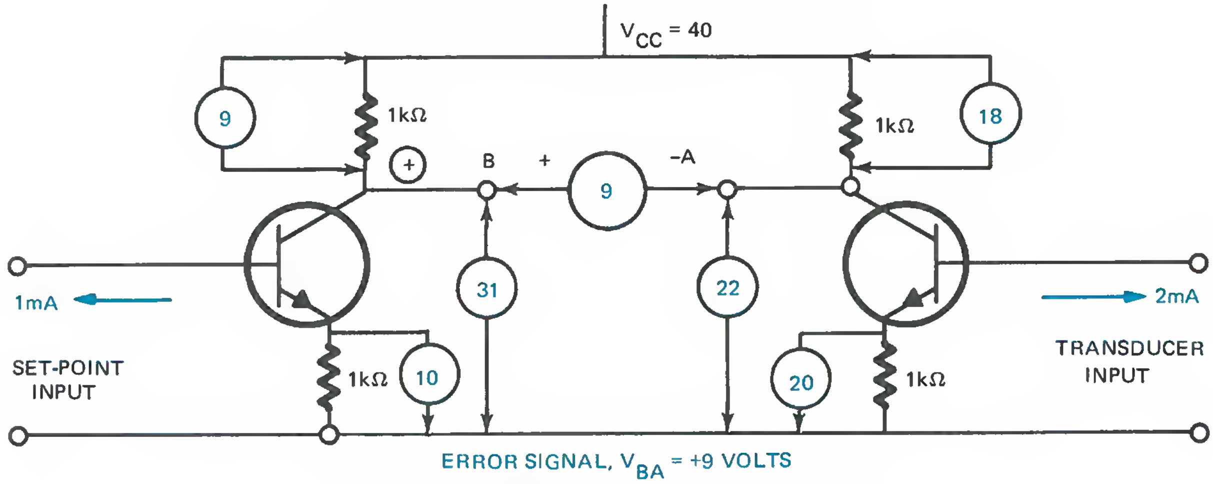
Another method of electronic error generation is shown in figure 4–3. The differential amplifier consists of two equal *gain* transistors, Q_1 and Q_2. The set-point output is connected to the base of Q_1 and the transducer output is connected to the base of Q_2. The differential amplifier is a DC amplifier employing direct coupling.

In analyzing how the basic amplifier operates, assume $R_{C1} = R_{C2} = R_{E1} = R_{E2} = 1k$, the transistors Q_1 and Q_2 have an equal current gain of about 9, and the set-point voltage causes 1 mA of base current in Q_1. When the controlled variable is at the desired operating value, the base current of Q_2 is 1 mA. The output error signal is 0 volts as shown in figure 4-4A.

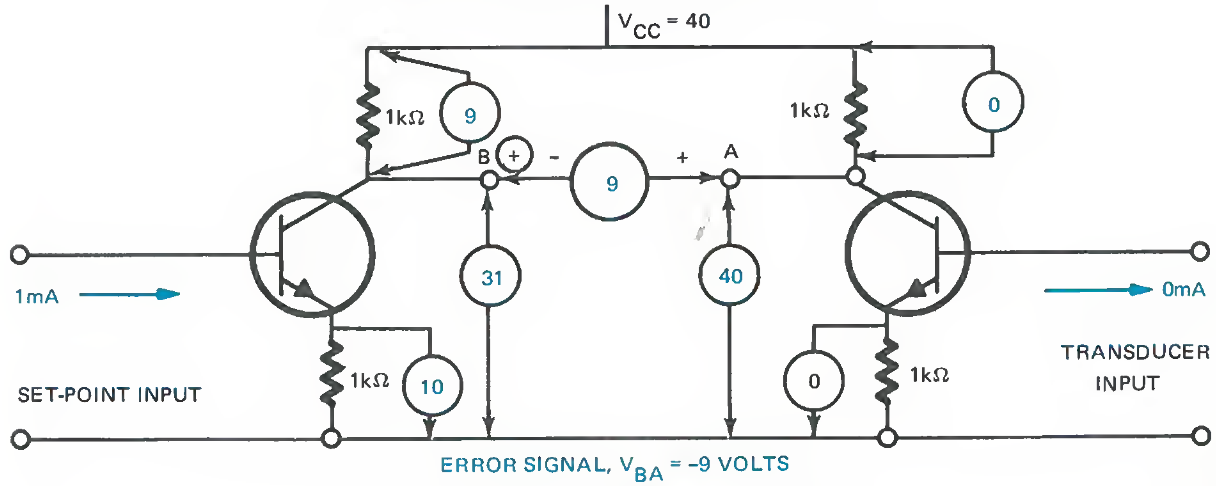
If the transducer input increases, causing the base current of Q_2 to double, the output error signal is +9 volts as shown in figure 4-4B. If the transducer input decreases to zero, the output error signal is -9 volts as shown in figure 4-4C. Thus, the differential amplifier may be used to generate an error signal that reflects the amplitude of the deviation between the transducer output and the set-point, as well as the direction of the deviation.



(A) TRANSDUCER INPUT EQUAL SET-POINT INPUT



(B) TRANSDUCER INPUT GREATER THAN SET-POINT



(C) TRANSDUCER INPUT LESS THAN SET-POINT

Fig. 4-4 Differential Amplifier Operation

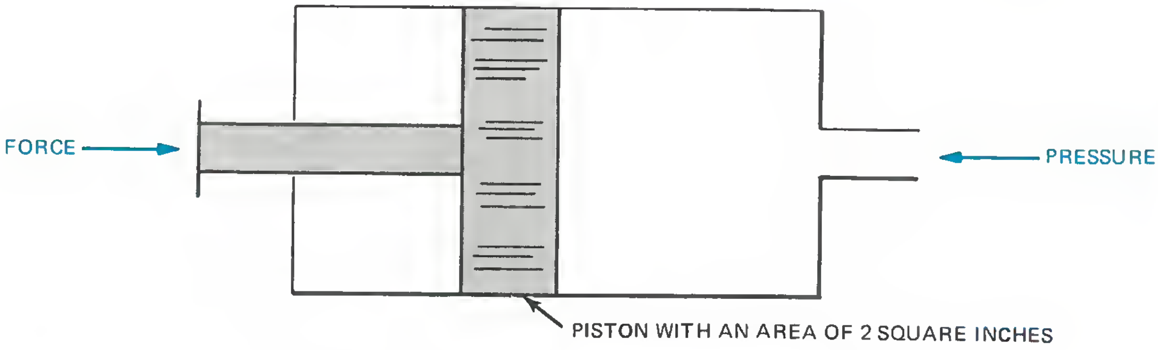


Fig. 4-5 Simple Force-Balance Mechanism

In a pneumatic or hydraulic controller, the error may be generated by a force-balance mechanism or a moment-balance mechanism. A simple force-balance mechanism is shown in figure 4-5. If the two forces are balanced, the piston does not move. For static balance, the force acting toward the right equals the force acting toward the left. For example, if the force acting toward the right is 100 lbs, the force acting to the left must be 100 lbs. The pressure required for balance is

$$\boxed{\Sigma f_R = \Sigma f_L} \tag{4.1}$$

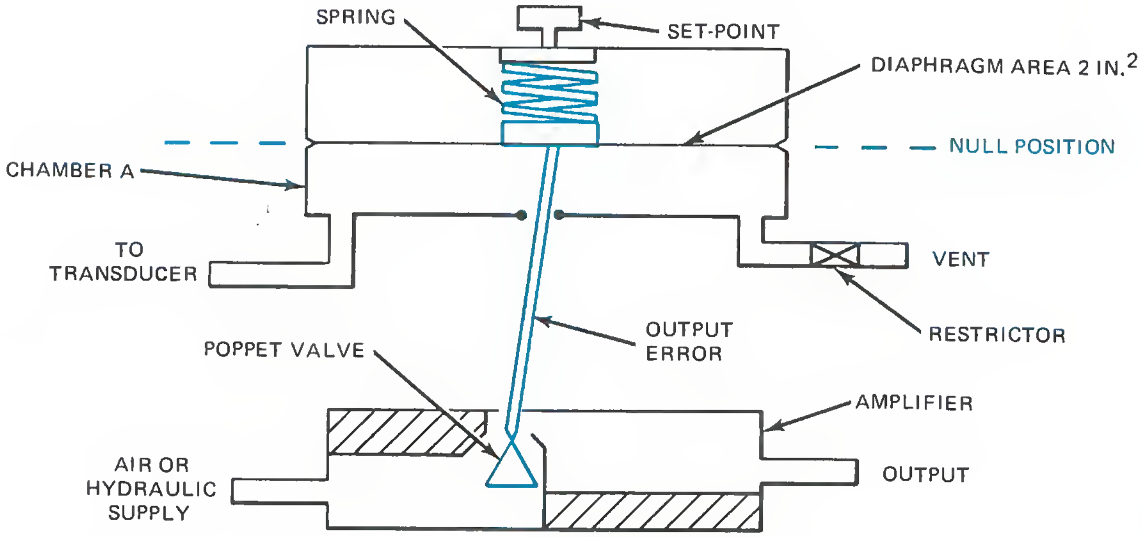
$$\Sigma f_R = \Sigma f_L = 100 \text{ lbs}$$

$$\boxed{\Sigma f_L = PA} \tag{4.2}$$

$$P = \frac{\Sigma f_L}{A}$$

$$P = \frac{100 \text{ lbs}}{2 \text{ in.}^2} = 50 \text{ psi}$$

A force-balance mechanism using a diaphragm or a flexible bellows as the piston is shown in figure 4-6. The spring, with a spring



4-6 Force-Balance Mechanism and Amplifier

constant of 100 lbs/in., is compressed 1 in. to exert a force of 100 lbs on the diaphragm. The movement of the diaphragm controls the poppet valve of the fluid amplifier. When the controlled variable is at the desired operating value, the output of the transducer must be

$$\boxed{\Sigma F_{up} = \Sigma F_{down}}$$

$$\Sigma F_{down} = 100 \text{ lbs}$$

$$\Sigma F_{up} = PA$$

$$P = \frac{\Sigma F_{up}}{A} = \frac{100 \text{ lbs}}{2 \text{ in.}^2} = 50 \text{ psi}$$

for a balanced condition. When this balance is attained, the poppet valve inlet is practically closed. This valve is not fully closed because the vent is permitting a small amount of pressure to bleed off.

If the output of the transducer increases to 100 psi, the diaphragm will move upward until the forces are again balanced. The distance the diaphragm moves up from the null or zero deviation position is

$$\Sigma F_{up} = \Sigma F_{down}$$

$$\Sigma F_{up} = PA = 100 \text{ psi} \times 2 \text{ in.}^2 = 200 \text{ lbs}$$

$$\Sigma F_{down} = 200 \text{ lbs}$$

$$\boxed{x = f/k} \qquad (4.3)$$

$$x = \frac{200 \text{ lbs}}{100 \text{ lb/in.}} = 2 \text{ inches}$$

The poppet valve will move upward 1 inch, reducing the output of the amplifier.

Now suppose that the output of the transducer is decreased to 25 psi. The diaphragm will move downward until the forces are again balanced. The distance the diaphragm moves down from the null or zero deviation position is

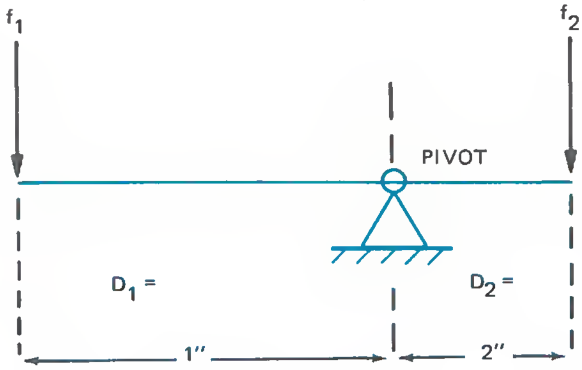


Fig. 4-7 Simple Moment-Balance Mechanism

$$\Sigma F_{up} = \Sigma F_{down}$$

$$\Sigma F_{up} = PA = 25 \text{ psi} \times 2 \text{ in.}^2 = 50 \text{ lbs}$$

$$\Sigma F_{down} = 50 \text{ lbs}$$

$$x = \frac{F}{k} = \frac{50 \text{ lbs}}{100 \text{ lb/in.}} = 1/2 \text{ inch}$$

The poppet valve will move downward from the null position 1/2 inch, increasing the output of the amplifier. Thus, the force-balance detector may be used to generate an error signal that reflects the amplitude of the deviation, as well as its direction.

A simple movement balance mechanism is shown in figure 4-7. If the movement in the clockwise direction is equal to the movement in the counterclockwise direction, the mechanism is in balance and no movement occurs. The product of the force exerted by f_1 multiplied by the moment arm (distance from pivot to the point the force is applied) is termed a moment.

For example, if the force f_1 acting counterclockwise is 100 lbs, f_2 acting clockwise for

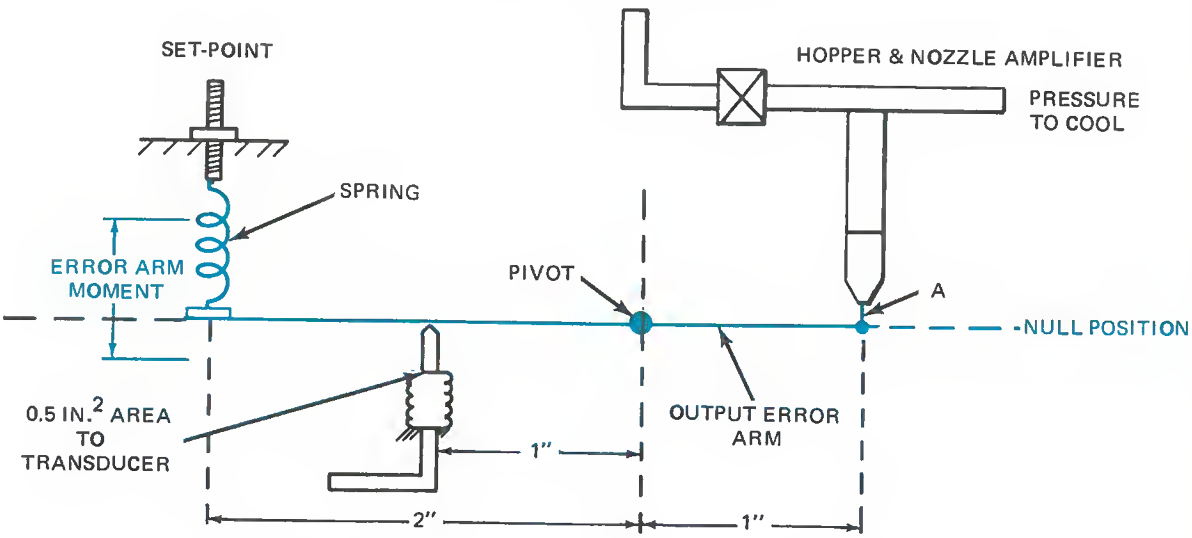


Fig. 4-8 Moment-Balance Mechanism and Amplifier

balance must be

$$\boxed{\Sigma M_{ccw} = \Sigma M_{cw}} \qquad (4.4)$$

$$\boxed{\Sigma M_{ccw} = FD} \qquad (4.5)$$

$$\Sigma M_{ccw} = 100 \text{ lb} \times 2 \text{ in.} = 200 \text{ lb-in.}$$

$$\Sigma M_{cw} = f_2 D_2$$

$$f_2 D_2 = 200 \text{ lb-in.}$$

$$f_2 = \frac{200 \text{ lb-in.}}{1 \text{ in.}} = 200 \text{ lbs}$$

A moment-balance mechanism is shown in figure 4-8. The spring, with a spring constant of 100 lb/in., is compressed 1 inch to exert a force of 100 lbs in a clockwise direction. When the controlled variable is at the desired operating value, the output of the transducer must be

$$\Sigma M_{ccw} = \Sigma M_{cw}$$

$$\Sigma M_{cw} = fD = 100 \text{ lbs } 2'' = 200 \text{ lb-in.}$$

$$\boxed{\Sigma M_{ccw} = (PA)\,D} \qquad (4.6)$$

$$P = \frac{\Sigma M_{ccw}}{AD} = \frac{200 \text{ lb-in.}}{(0.5 \text{ in.}^2)\ 1 \text{ in.}}$$

$$P = 400 \text{ psi}$$

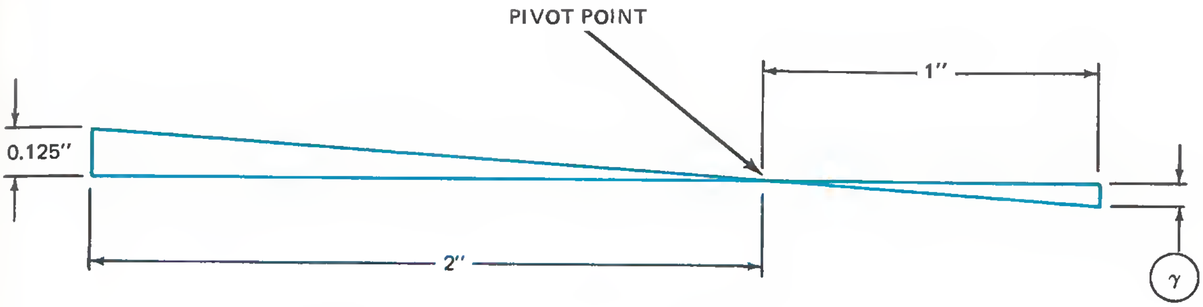
If the output of the transducer increases to 450 psi, the output arm moves clockwise until the moments are again equal. The distance the arm moves clockwise from null position or zero deviation position is

$$\Sigma M_{cw} = \Sigma M_{ccw}$$

$$\Sigma M_{cw} = (PA)\,D$$

$$\Sigma M_{cw} = 450 \frac{\text{lbs}}{\text{in.}^2} \times 0.5 \text{ in.}^2 \text{ (1 in.)} = 225 \text{ lbs-in.}$$

$$\Sigma M_{ccw} = fD = (k\chi)\,D$$



$$\frac{\gamma}{1''} = \frac{0.125''}{2.00''} \qquad y = \frac{0.125''\ (1'')}{2.00''} = 0.0625 \text{ INCHES}$$

Fig. 4-9 Hopper and Nozzle Clearance

$$\chi = \frac{\Sigma M_{ccw}}{kD} = \frac{225 \text{ lb-in.}}{(100 \text{ lb/in})\ 2''} = 1.125 \text{ inches CW}$$

The output error arm will move -.125 inch CW (1.00 - 1.125) reducing the pressure to the load.

If the output of the transducer decreases to 350 psi, the output arm moves counterclockwise until the moments are again equal. The distance the arm moves counterclockwise from the null or zero deviation position is

$$\Sigma M_{cw} = \Sigma M_{ccw}$$

$$\Sigma M_{cw} = (PA)\ D$$

$$\Sigma M_{cw} = 350 \text{ psi} \times 0.5 \text{ in.}^2\ (1 \text{ in.})$$

$$\Sigma M_{cw} = 175 \text{ lbs-in.}$$

$$\Sigma M_{ccw} = fD = (k\chi)\ D$$

$$\chi = \frac{\Sigma M_{ccw}}{kD} = \frac{175 \text{ lbs-in.}}{\left(100 \frac{\text{lb}}{\text{in.}^2}\right) 2''}$$

$$\chi = 0.875 \text{ inches CCW}$$

The output error arm will move 0.125 inch CCW (1-0.875), increasing the pressure to the load. The clearance between the flapper and nozzle (point A to nozzle) can be approximately calculated using the diagram in figure 4-9.

MATERIALS

1 Scale, 0-10 cm
1 Spring, approximately 3/4 inch diameter, 2 inch length
1 Bellows assembly, 1 inch diameter
1 Regulator, air pressure 0-100 psi
1 Gage, air pressure 0-100 psi
1 Supply, air pressure 0-100 psi
1 Valve, manual shut-off
1 Pointer and indicator assembly
Miscellaneous hoses, fittings, nuts and bolts

PROCEDURE

1. Construct the experimental setup shown in figure 4-10.
2. Adjust the set-point until the spring length is approximately 2.0 inches (slightly compressed).

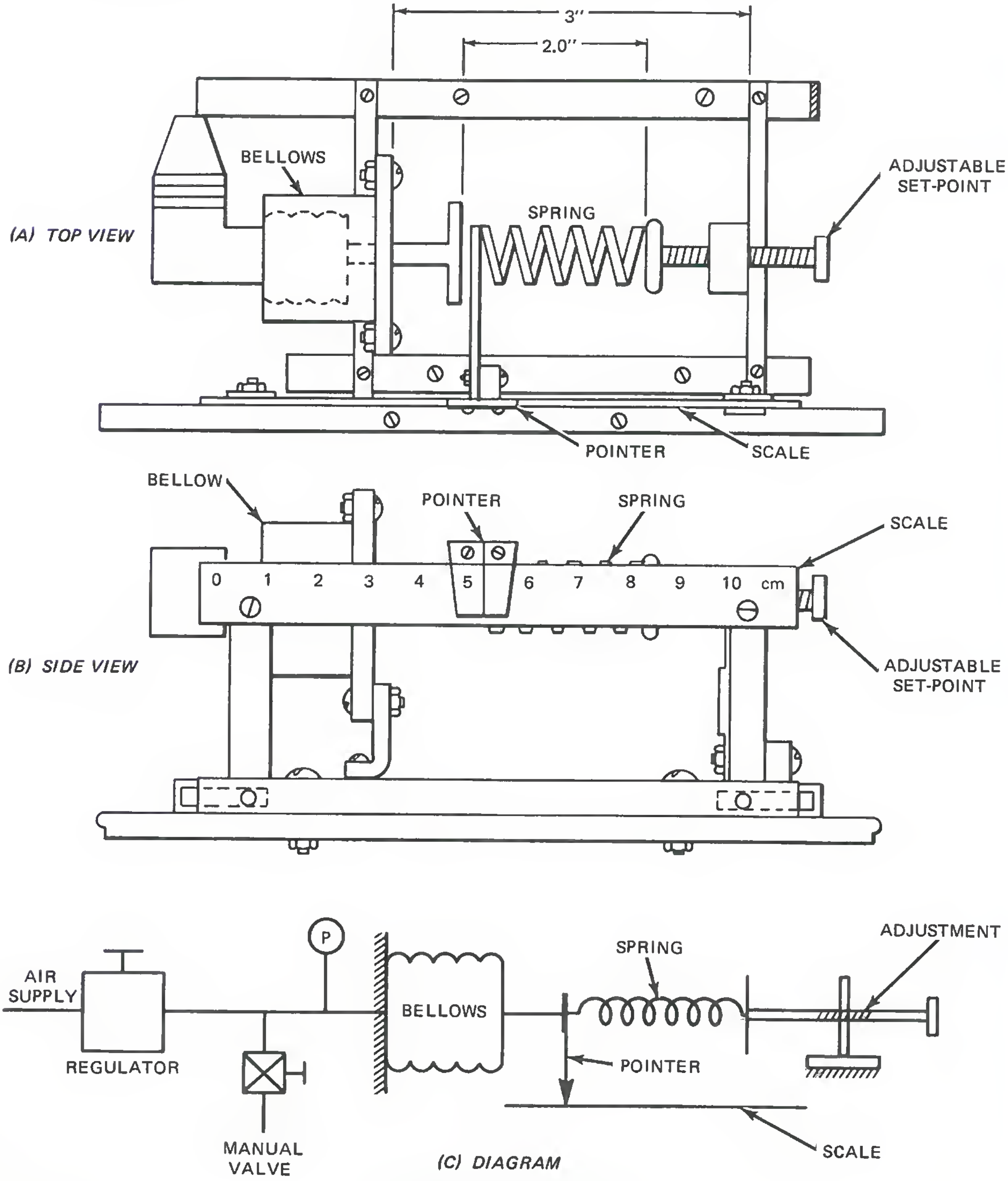


Fig. 4-10 Test Setup

Pressure psi	Deflection in cm	F_R in lbs	F_L in lbs
0	0		
10			
10			
20			
30			
40			
50			
60			
70			
80			
90			

Fig. 4-11 The Data Table

3. Adjust the scale position, to the right or left, until the hairline pointer is over a convenient number.
4. Adjust the pressure regulator to 10 psi as indicated by the gage.
5. Read and record the amount of deflection of the hairline pointer in the Data Table, figure 4–11.
6. Calculate the force at each pressure reading exerted by the bellows assembly using the following equation where A is the area of bellows:

$$f_R = PA.$$

7. Record these in the Data Table as f_R.
8. Repeat steps 4, 5 and 6 in 10 psi increments.
9. Calculate the spring constant using the following equation:

$$k = \Delta f/\Delta_X$$

where Δf is the force f_R at 100 psi and Δ_X is the total deflection in inches.

10. Calculate the force at each pressure reading exerted by the spring assembly using the following equation:

$$f = k_x$$

11. Record these data in the Data Table as F_L.

ANALYSIS GUIDE. Using the data from the data table, plot the pressure versus the deflection of the pointer. Plot a graph of the force exerted by bellows versus the force exerted by the spring. Discuss how the device in the experiment may be used as an error detector.

PROBLEMS

1. The ratio network in figure 4-12 has the following values: $R_1 = R_2 = R_3 = R_4 = R_5 = 350$ ohms. Determine the thevenin equivalent circuit for the network assuming the internal resistance of set-point device and the transducer are negligible.

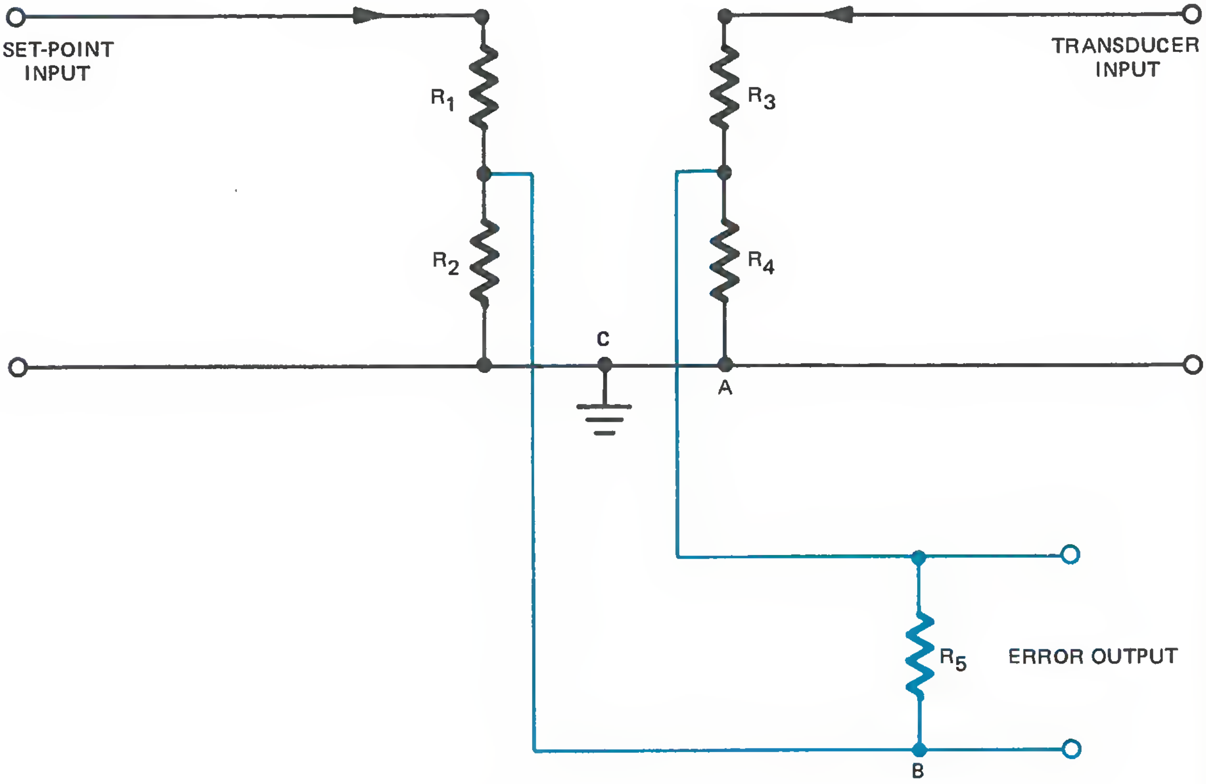


Fig. 4-12 Ratio Network For Error Generation

2. In problem 1, the set-point is 2 volts and the transducer input is 1 volt. Calculate the error output volate, V_{AB}.

3. The simple force balance mechanism in figure 4-5 has a pressure of 25 psi applied. Calculate the force required for the piston to be stopped.
4. The simple moment balance mechanism in figure 4-7 has a force f_1 of 50 lbs and f_2 of 25 lbs. Determine the distance from the pivot to force f_2 required for balance.
5. What type of feedback (positive or negative) is used in the mechanism shown in figure 4-8?

experiment 5 ELECTRONIC CONTROLLERS

INTRODUCTION. The controller is the brain of an automatic control system. It determines the difference between the desired condition and the actual condition and drives the actuator to reduce this difference to zero. In this experiment, an electronic amplifier used as a controller will be examined.

DISCUSSION. An electronic controller must have sufficient sensitivity (gain) to respond to a low-level error signal and must produce sufficient output to satisfactorily drive the control system actuator. Vacuum tube, gas tube, magnetic and solid state controllers (amplifiers) are commonly used throughout industry. The overall performance of a control system is determined by the characteristics of the amplifier, particularly with respect to gain and frequency response. Since the error signal can be either AC or DC, the amplifier must be suitable for the type of signal produced and must provide a suitable otuput to the actuator.

A controller having a DC error signal and a DC actuator is shown in figure 5-1A. Q_1 and Q_2 form a differential amplifier. Q_3 and Q_4 are peramplifiers used to drive the power amplifier, Q_5 or Q_6 respectively. Q_5 *or* Q_6 energizes a DC motor control relay, which in turn controls the direction of rotation of the motor.

When the voltage measured from the wiper of R_1 equals the voltage measured from the wiper of R_2 transistors Q_1 and Q_2 conduct equally. Therefore, the voltage measured from the collector of Q_1 to the collector of Q_2 is zero. With zero base-to-emitter bias, Q_3 and Q_4 aid cutoff and the output of both power amplifiers is zero.

If the voltage at the wiper of R_1 increases, transistor Q_1 conducts more than Q_2 and the voltage at its collector decreases. The voltage from the collector of Q_2 to collector of Q_1 becomes positive and forward biases Q_4 and reverse biases Q_3. Q_4 drives Q_6 sufficiently to energize relay 2. The closing of relay 2 causes the motor, which is mechanically coupled through a gear train to the load and the follow-up potentiometer R_2, to rotate in one direction. The rotation is such that the voltage at the wiper of R_2 increases. The motor-rotation continues until the voltage from the collector of Q_1 to Q_2 is zero, and the error signal is also zero.

If the voltage at the wiper of R_1 decreases, transistor Q_1 conducts less than Q_2 and the voltage at its collector increases. The voltage from the collector of Q_1 to the collector of Q_2 becomes positive and forward biases Q_3. This energizes relay 1 causing the motor to drive in the other direction until a balance is obtained.

The input potentiometer R_1 could be a gyro input of an automatic missile control system, or a variable set-point input of an automatic process system. The motor is the system or process actuator, while the potentiometer is the process transducer. Figure 5-1B shows the block diagram of the DC automatic control system or process.

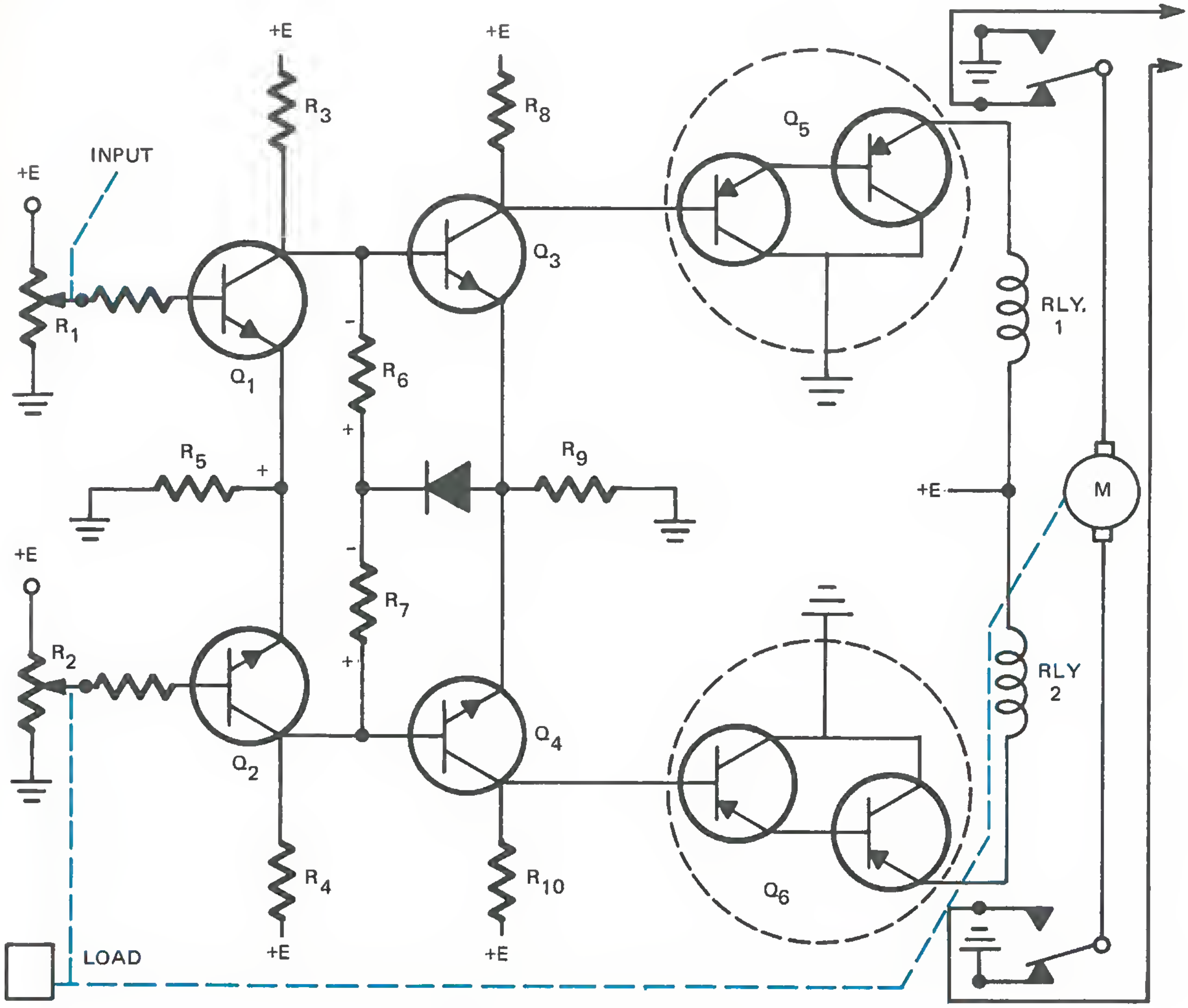
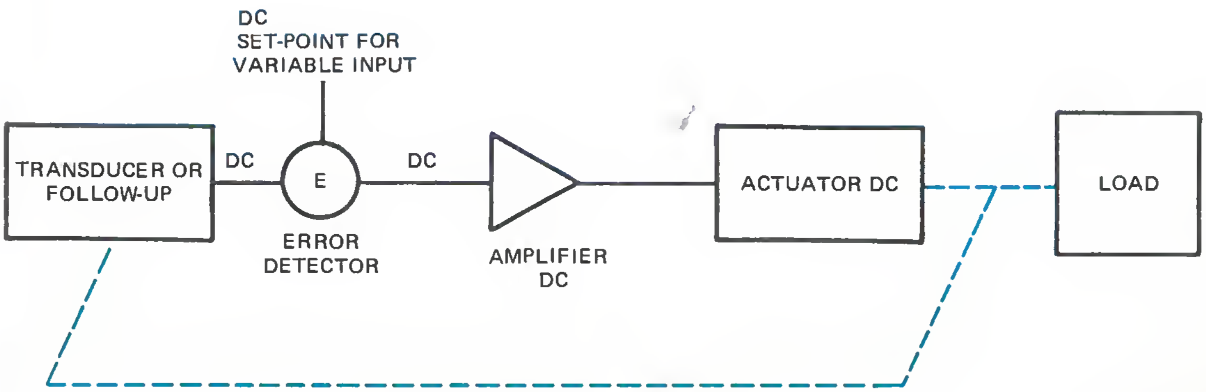


Fig. 5-1A Electrical Schematic



(B) BLOCK DIAGRAM

Fig. 5-1B Controller System with a DC Error Signal and a DC Actuator

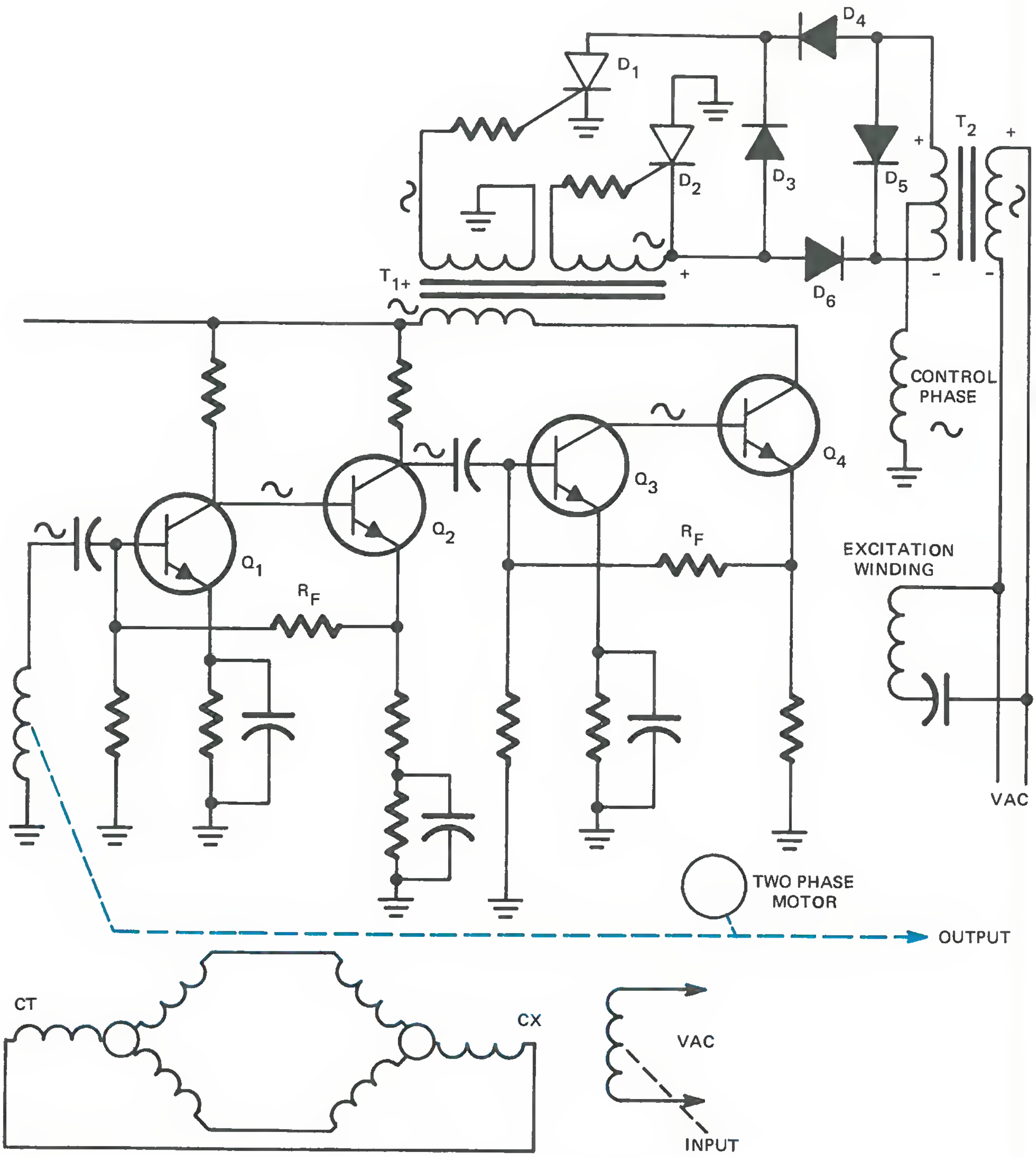
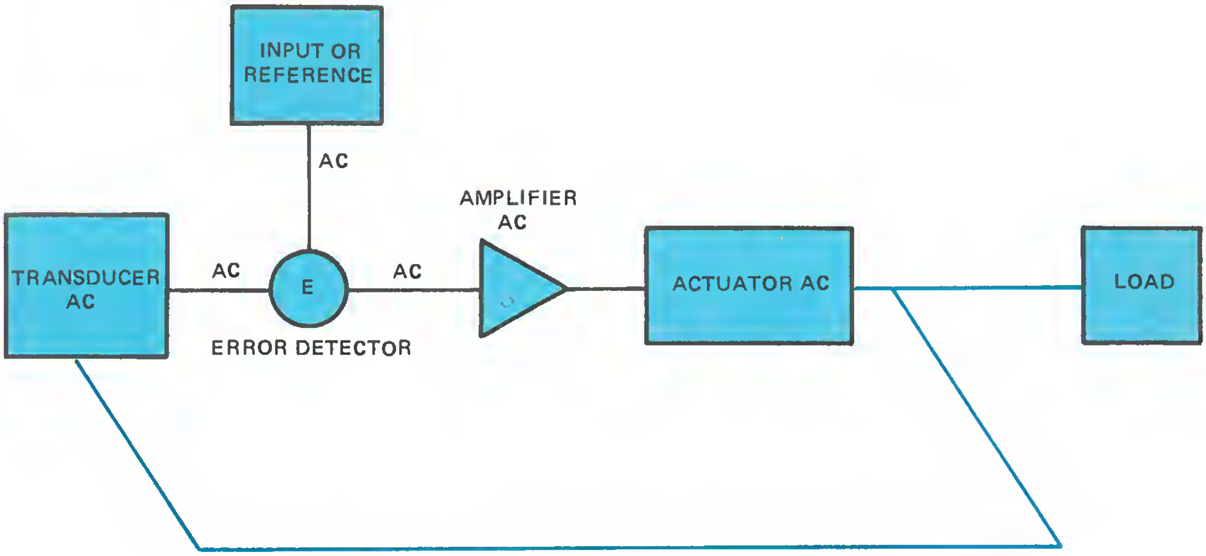


Fig. 5-2A Electrical Schematic

A controller having an AC error signal and an AC actuator is shown in figure 5-2A. Q_1 and Q_2 are preamplifiers. Q_3 is a driver amplifier that drives the output power amplifier Q_4. Q_4 is transformer-coupled to a pair of SCRs that drive the control winding of a two-phase servo motor. The servo motor is mechanically coupled to the load and to the rotor of the control transformer.

With the control transmitter and the con-



(B) BLOCK DIAGRAM

Fig. 5-2B Controller System with an AC Error Signal and an AC Actuator

trol transformer synchro rotors at zero mechanical degrees, the voltage induced into the rotor windings of the control transformer is zero. Under these conditions the speed of the two-phase servo motor is also zero.

When the rotor of the control transmitter is rotated clockwise, an error signal is developed in the rotor winding of the control transformer. This AC error signal is amplified by Q_1, Q_2, Q_3, and Q_4. The output of the power amplifier Q_4 is transformer-coupled to the gates of the SCRs. The SCRs control the direction of rotation and speed of the control motor.

The voltage induced into the secondary of T_1 fires the SCRs in such a manner that the voltage developed across the control winding of the motor is leading the excitation voltage by 90 degrees. This phase relationship causes the motor to rotate in one direction. Since the motor is mechanically geared to the rotor of the control transformer, the rotation of the motor drives the rotor in the clockwise direction, and the voltage induced in the control transformer motor winding decreases to zero. Should the rotor of the control transmitter be rotated counterclockwise, an error signal is developed in the rotor windings of the control transformer that is 180° out of phase with the signal that was generated with the clockwise rotation. This error signal is amplified and coupled to the gates of the SCRs in such a manner that the voltage developed across the control phase of the motor is 90° leading the excitation voltage. This phase relationship causes the motor to rotate in the other direction. The rotation of the motor drives the rotor of the control transformer in a counterclockwise direction and the voltage induced in the rotor winding decreases to zero.

The shaft of the control transmitter is the variable reference or input to the control system. The motor is the system actuator, while the control transformer is the system follow-up synchro or transducer. Figure 5-2B shows the block diagram of the automatic control system.

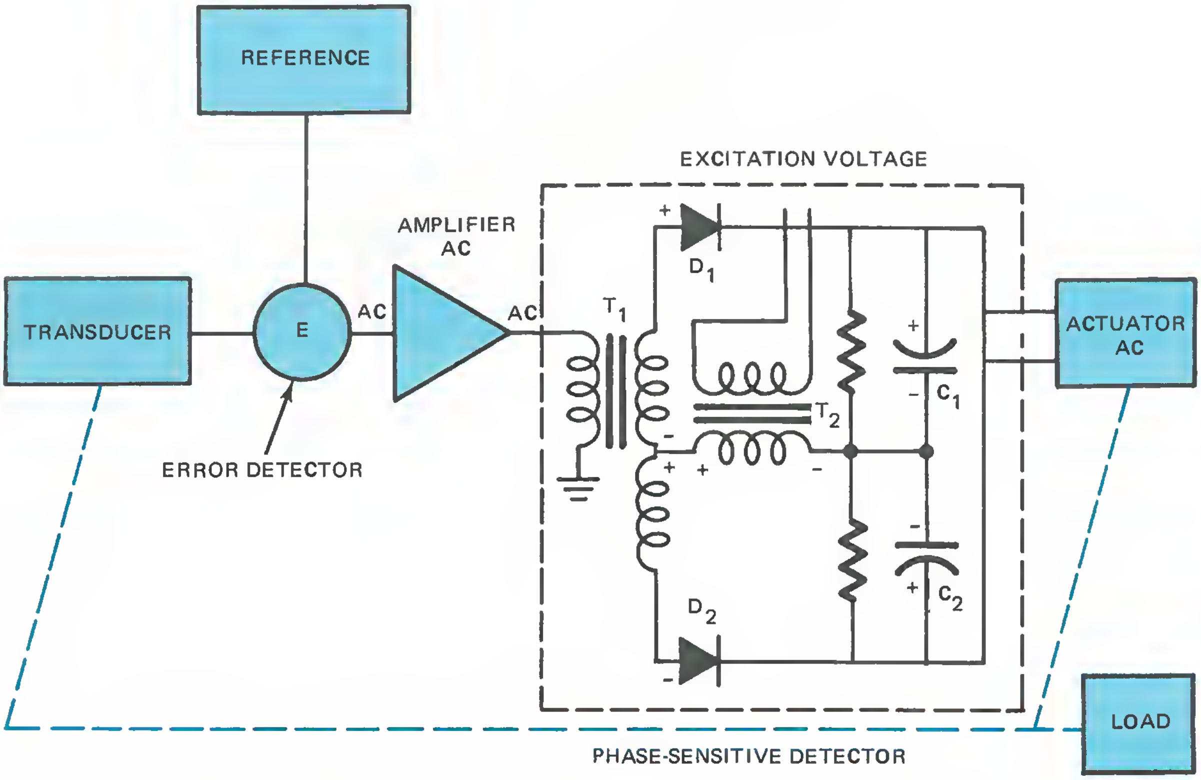


Fig. 5-3 Controller System with AC Error Signal and a DC Actuator Utilizing a Phase-Sensitive Detector

A controller having an AC error signal input and a DC actuator is shown in figure 5-3. The AC amplifier and transducer is the usual type, but employs a phase-sensitive detector to produce a DC voltage whose polarity depends upon the phase of the AC error signal. Both diodes, D_1 and D_2, conduct during the half-cycle of excitation when the polarity of transformer T_2 is as shown. When an AC error signal is applied to transformer T_1, the diodes do not conduct equally. When the induced voltage in the secondary T_1 has the polarity shown, diode D_1 conducts more current than diode D_2. A greater charge builds upon capacitor C_1 than on capacitor C_2; hence, the DC output is as shown in the figure. This voltage polarity causes the DC actuator voltage to rotate in one direction. If the error voltage applied to transformer T_1 had been of opposite phase, diode D_2 would have conducted more current than diode D_1. As a result, the charge on capacitor C_2 would have exceeded that of C_1. The DC output voltage would have been of the opposite polarity and the motor would have rotated in the other direction. During the half-cycles of excitation when the polarity of T_2 is opposite that shown, both diodes would be reverse biased. Capacitors C_1 and C_2 maintain the DC output essentially constant during these half cycles. The excitation voltage at the secondary of T_2 should be greater in amplitude than the error voltage induced into the secondary of T_1.

Direct-coupled amplifier stages may be used in conjunction with an error detector that produces a DC output. Such amplifiers tend to be unstable with respect to tempera-

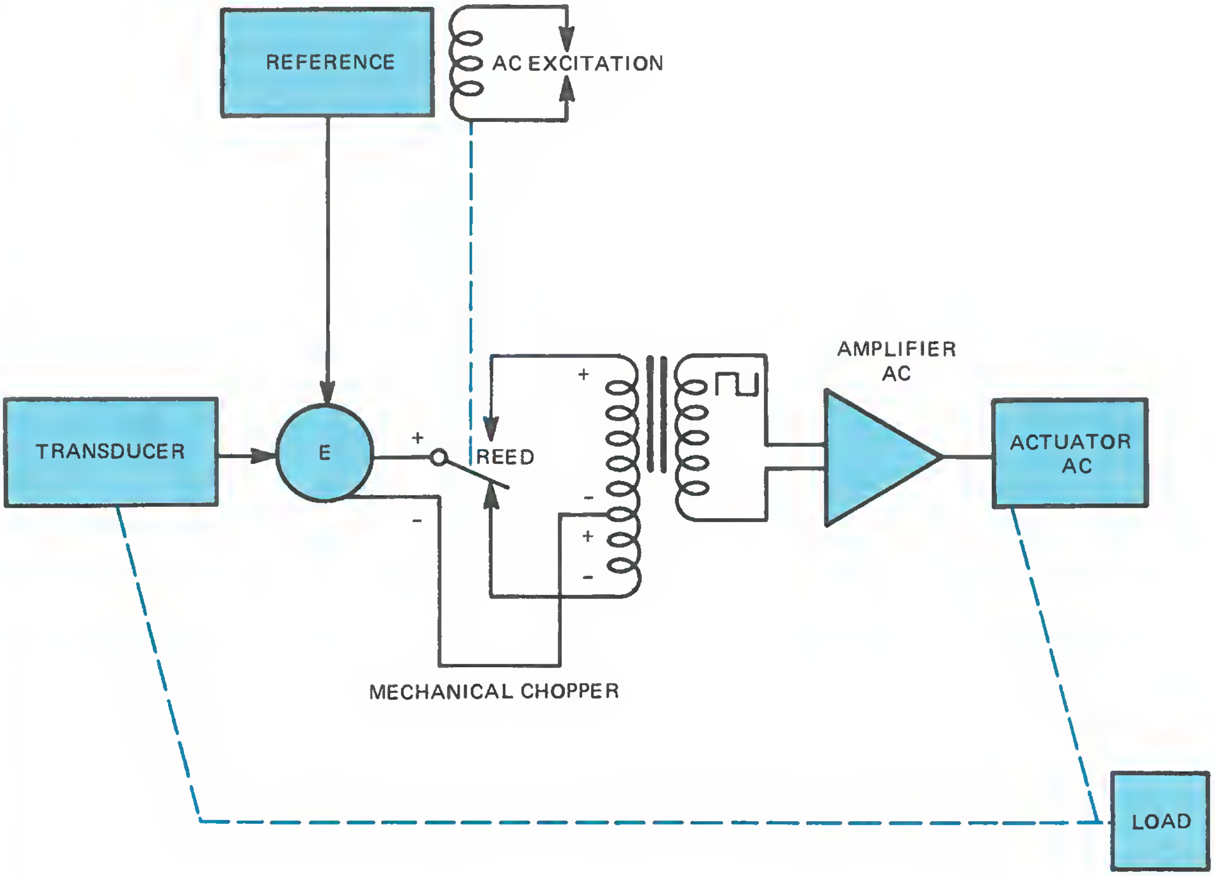


Fig. 5-4 Controller System with a DC Error Signal and an AC Actuator Utilizing a Chopper

ture and supply voltage variations. For this reason, choppers are used to convert the DC error signal to an AC signal, permitting the use of R-C or transformer-coupled amplifier stages. A controller having a DC error signal and an AC actuator is shown in figure 5-4. The chopper can be an electromechanical device or an electronic circuit. Sometimes the chopper is called a modulator. The sinusoidal excitation applied to the driving coil of the chopper causes a metal reed to vibrate between two fixed contacts. The contacts are connected to opposite ends of the transformer. The DC error voltage is applied between the reed and the center tap of the transformer. As the reed vibrates, it converts the error voltage alternately to the opposite ends of the transformer winding. When the reed is in the upper position, the current flows upward through the upper half of the transformer winding. A short time later the reed is in the lower position and the current flows downward through the lower half of the transformer winding. This periodic reversal of current direction through the primary of the transformer causes, an AC voltage to be induced into the secondary. The amplitude and phase of the square wave are dependent on the amplitude and polarity of the DC error signal. The length of time the vibrating reed rests on the fixed contact is known as the dwell time. After the DC error voltage has been converted to an AC waveform, it can be applied to a conventional AC amplifier.

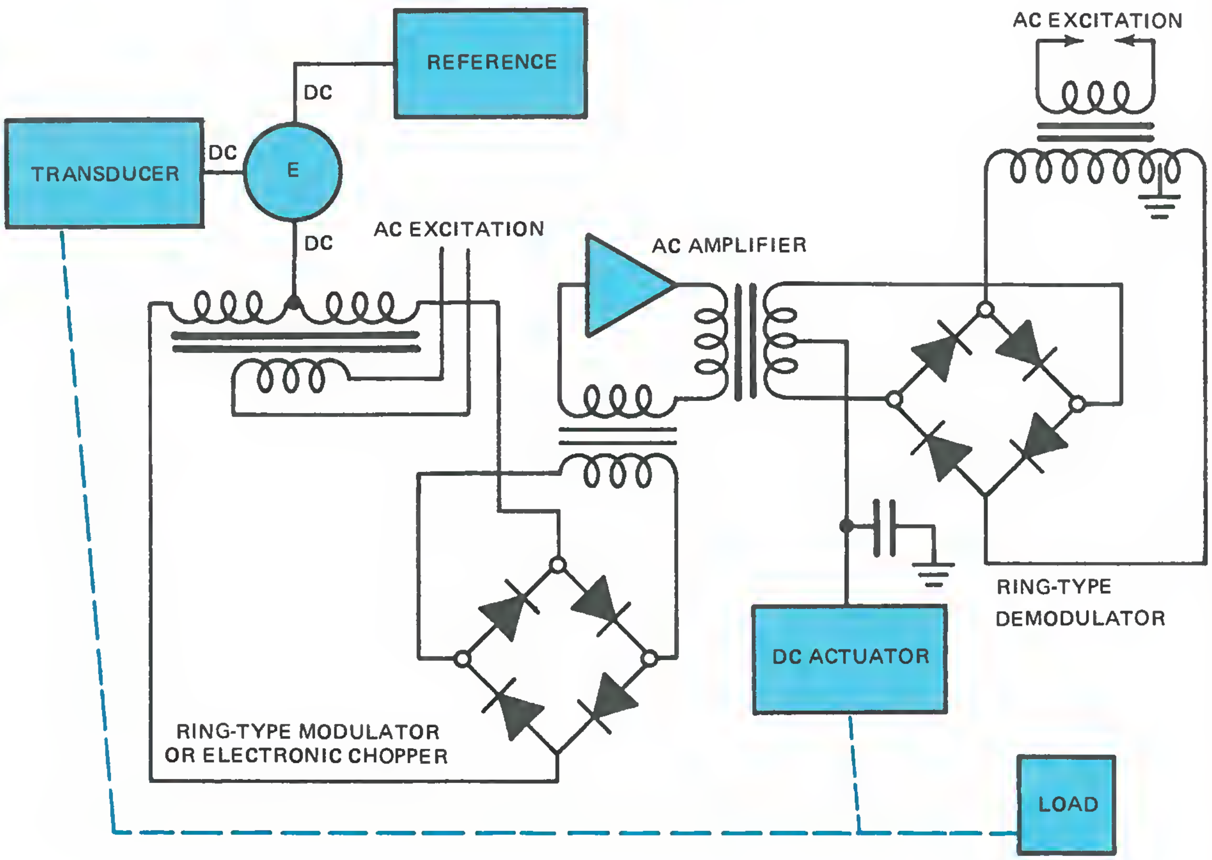


Fig. 5-5 Controller System with a DC Error Signal and a DC Actuator

Another method that could be used is shown in figure 5-5. In this circuit the DC error signal is fed to a ring modulator that converts the DC to AC. The AC signal is amplified and fed to a ring demodulator. The ring demodulator produces the required DC output to the actuator.

Hydraulic, pneumatic, and other types of amplifiers with feedback exhibit characteristics similar to electronic amplifiers with feedback, and for this reason, a study of electronic amplifiers with feedback will be pursued. Figure 5-6 shows an amplifier in which a fraction, β, of the output voltage is fed back and added to the input.

With *negative feedback,* an amplifier

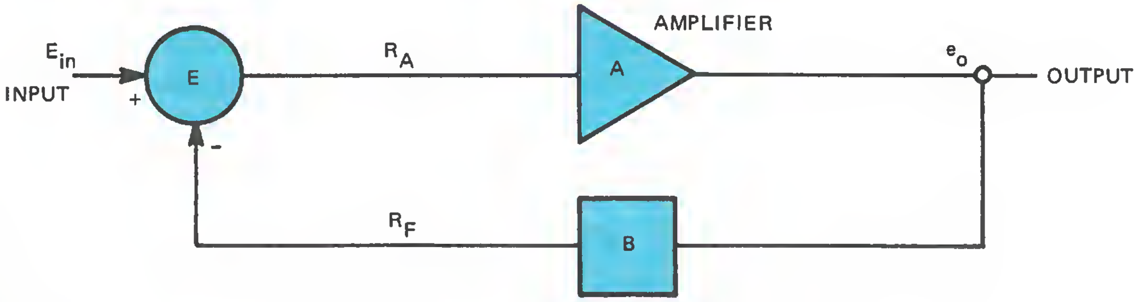


Fig. 5-6 Amplifier Circuit Using Feedback

having a high value of gain can be used in a way that will exhibit parameters that are independent of the amplifying device and supply voltage variations. Referring again to figure 5-6, the feedback voltage β may oppose the input voltage to give

$$e_a = e_{in} - e_f$$

But

$$e_f = \beta e_o$$

Therefore,

$$e_a = e_{in} - \beta e_o$$

and

$$e_o = Ae_a$$

$$e_o = A(e_{in} - \beta e_o)$$

$$e_o + A\beta e_o = Ae_{in}$$

$$e_o(1 + A\beta) = Ae_{in}$$

$$\frac{e_o}{e_{in}} = \frac{A}{1 + A\beta}$$

but

$$\frac{e_o}{e_{in}} = A' \text{ (the stage gain with feedback)}$$

$$\boxed{A' = \frac{A}{1 + A\beta}} \tag{5.1}$$

An amplifier circuit with a feedback ratio of 0.1 is used with an amplifier that has a gain of 1000. The gain of the amplifier circuit is

$$A' = \frac{1000}{1 + 1000\,(0.1)} = \frac{1000}{101} = 9.9$$

Should the gain of the amplifier change to 500 (a drastic reduction), the new value of the amplifier circuit gain is

$$A' = \frac{500}{1 + 500\,(0.1)} = \frac{500}{51} = 9.8$$

Therefore, the gain of an amplifier circuit with negative feedback is practically constant and is approximately

$$\boxed{A' = \frac{1}{\beta}} \tag{5.2}$$

Negative feedback also modifies the input impedance of the amplifier. Referring again to figure 5-6, assume the input resistance without feedback is R_{in}.

$$R_{in} = \frac{e_{in}}{i_{in}} = \frac{e_a}{i_{in}} \text{ and } i_{in} = \frac{e_a}{R_{in}}$$

But with feedback,

$$e_a = e_{in} - \beta e_o$$

$$e_a = e_{in} - \beta(Ae_a)$$

Collecting terms and solving for e_{in},

$$e_{in} = e_a(1 + \beta A)$$

$$R_{in}' = \frac{e_a(1 + \beta A)}{\frac{e_a}{R_{in}}} = (1 + \beta A)\,R_{in} \tag{5.3}$$

An amplifier circuit with a feedback ratio of 0.1 is used with an amplifier that has a gain of 1000 and an input resistance of 1 kilohm. The input resistance of the amplifier circuit is

$$R' = [1 + 0.1(1000)]\ 1\text{k}\Omega$$

$$R' = 101\ \text{k}\Omega$$

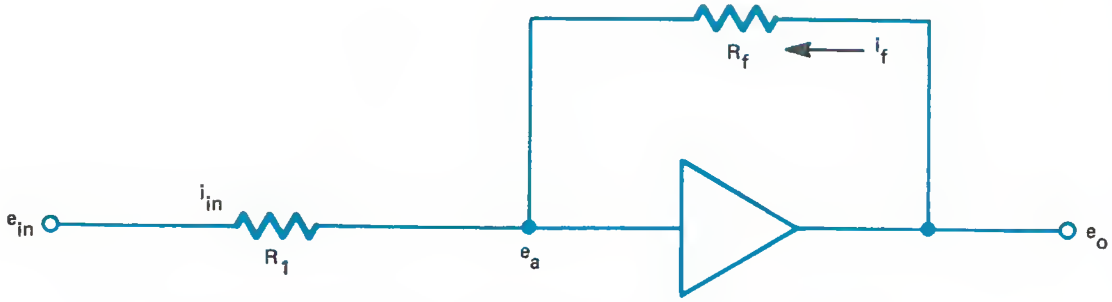


Fig. 5-7 Operation Amplifier Having Proportional Control

Thus, the input impedance of an amplifier with negative voltage feedback is increased by a factor of $(1 + \beta A)$.

An operational amplifier circuit used to obtain proportional control is shown in figure 5-7. The amplifier has a high value of gain, usually several thousand. This means that an extremely small variation in input voltage will move the output through its full range. To determine the output voltage of the circuit, assume the voltage e_a is zero and apply Kirckhoff's current law.

$$i_{in} + i_f = 0$$

Therefore,

$$\frac{e_{in}}{R_{in}} + \frac{R_o}{R_f} = 0$$

$$\frac{e_o}{R_f} = -\frac{e_{in}}{R_a}$$

$$\boxed{e_o = \frac{R_f}{R_{in}} e_{in}} \qquad (5.4)$$

Thus, the output of the circuit is proportional to $-R_f/R_{in}$ times the input. $-R_f/R_{in}$ is sometimes termed the proportionality constant or scale factor.

In many instances it is necessary to determine the algebraic sum of two or more signals. Figure 5-8 shows a summing amplifier which is receiving two inputs. The output of the circuit is

$$e_o = \frac{R_f}{R_1} e_1 - \frac{R_f}{R_2} e_2 \qquad (5.5)$$

Thus, e_o is the sum or difference of the inputs.

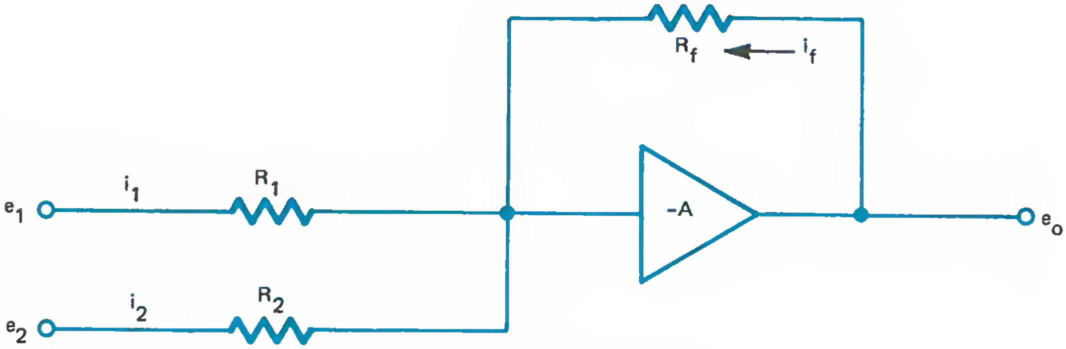


Fig. 5-8 A Summing Amplifier

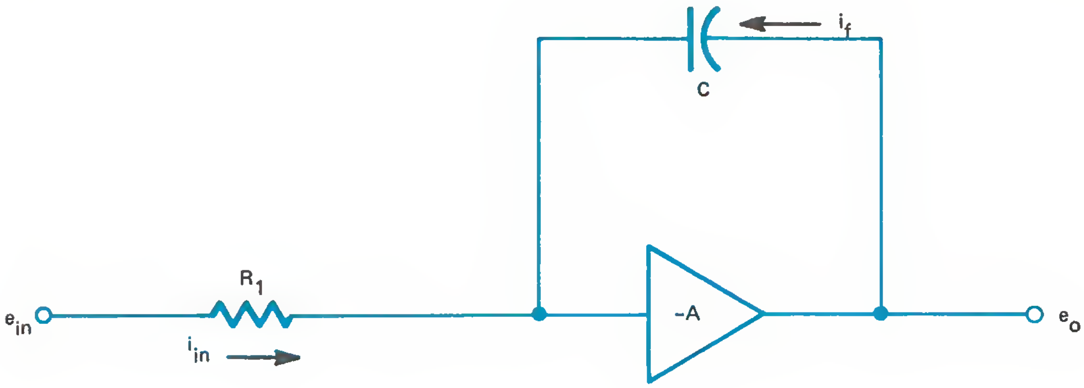


Fig. 5-9 An Integrating Amplifier

In some circuits, the output will vary with the time integral of the input. This type circuit, termed an integrator or reset amplifier, is shown in figure 5-9. The output of the circuit can be calculated by

$$i_{in} + i_f = 0$$

But

$$i_{in} = \frac{e_{in}}{R_1}$$

and

$$i_f = C\frac{de_o}{dt}$$

Therefore,

$$\frac{e_{in}}{R_1} + C\frac{de_o}{dt} = 0$$

$$\frac{e_{in}}{R_1} = -C\frac{de_o}{dt}$$

$$de_o = \frac{-1}{R_1C}\, e_{in}dt$$

$$\boxed{e_o = \frac{-1}{R_1C}\int e_{in}dt} \qquad (5.6)$$

Thus, e_o is the time integral of the input.

If the capacitor and resistor in figure 5-9 are interchanged as shown in figure 5-10, the

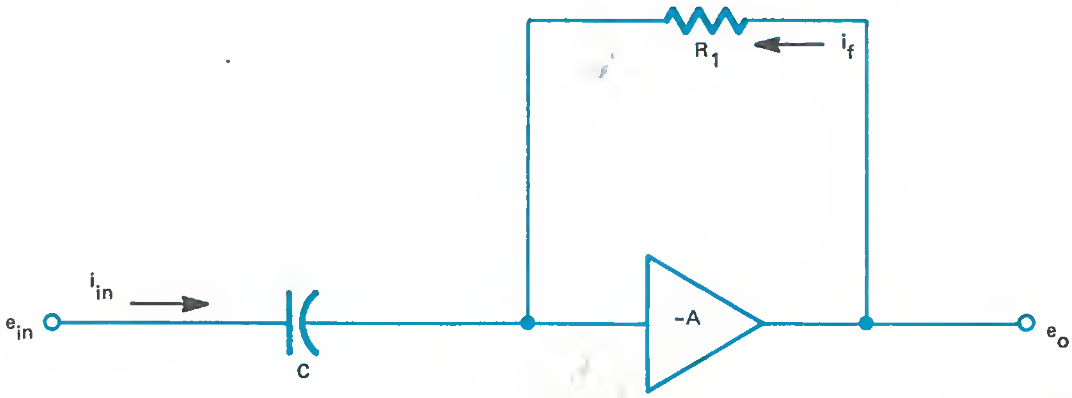


Fig. 5-10 A Differentiating Amplifier

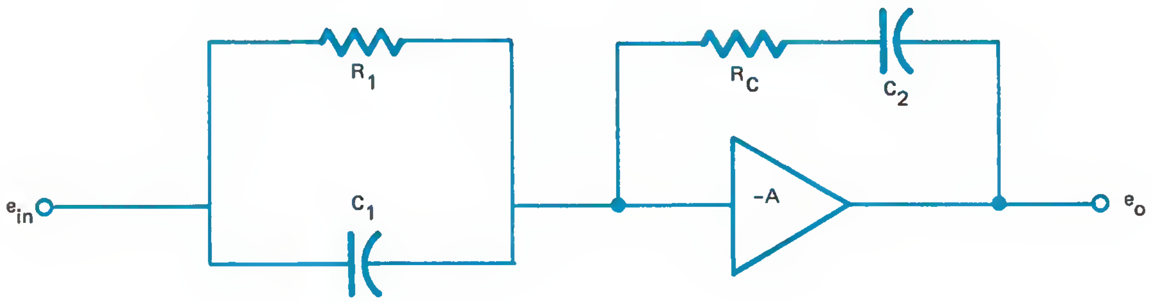


Fig. 5-11 A Proportional Plus Reset Plus Rate Amplifier System

circuit becomes a differentiator or rate circuit. The output signal of a differentiating amplifier is proportional to the rate of change of the input signal. The output of the circuit can be determined by

$$i_1 + i_f = 0$$

$$i_f = \frac{e_o}{R_1}$$

$$i_1 = C\frac{de_{in}}{dt}$$

$$\frac{e_o}{R_1} = -C\frac{de_{in}}{dt}$$

$$e_o = -R_1 C\frac{de_{in}}{dt}$$

Thus, the output is proportional to the derivative or rate of change of the input.

In an optimum control circuit, a combination of proportional, reset and rate action is desired. This effect can be obtained by using a combination of the foregoing circuits as shown in figure 5-11.

MATERIALS

2 DC power supplies, 0-40V
1 Audio generator, sine – square
2 Diodes, IN457 or equivalent
2 Transistors, 2N398 or equivalent
1 Transformer, 200 ohm primary and 500 ohm CT secondary
2 Resistors, 10kΩ 1/2W
5 Resistors, 1kΩ 1/2W
1 Resistor, 18kΩ 1/2W
1 Resistor, 22kΩ 1/2W
3 Capacitors, 100 μF 6 volts
1 Capacitor, 1 μF 12 volts
1 Oscilloscope

PROCEDURE

1. Construct the experimental circuit shown in figure 5-12A.
2. Adjust the frequency of the audio generator to 400 Hertz and the amplitude to a maximum.
3. Connect the DC power supply as shown in figure 5-12B to the input of the electronic chopper and adjust the voltage at point A to 2 volts.

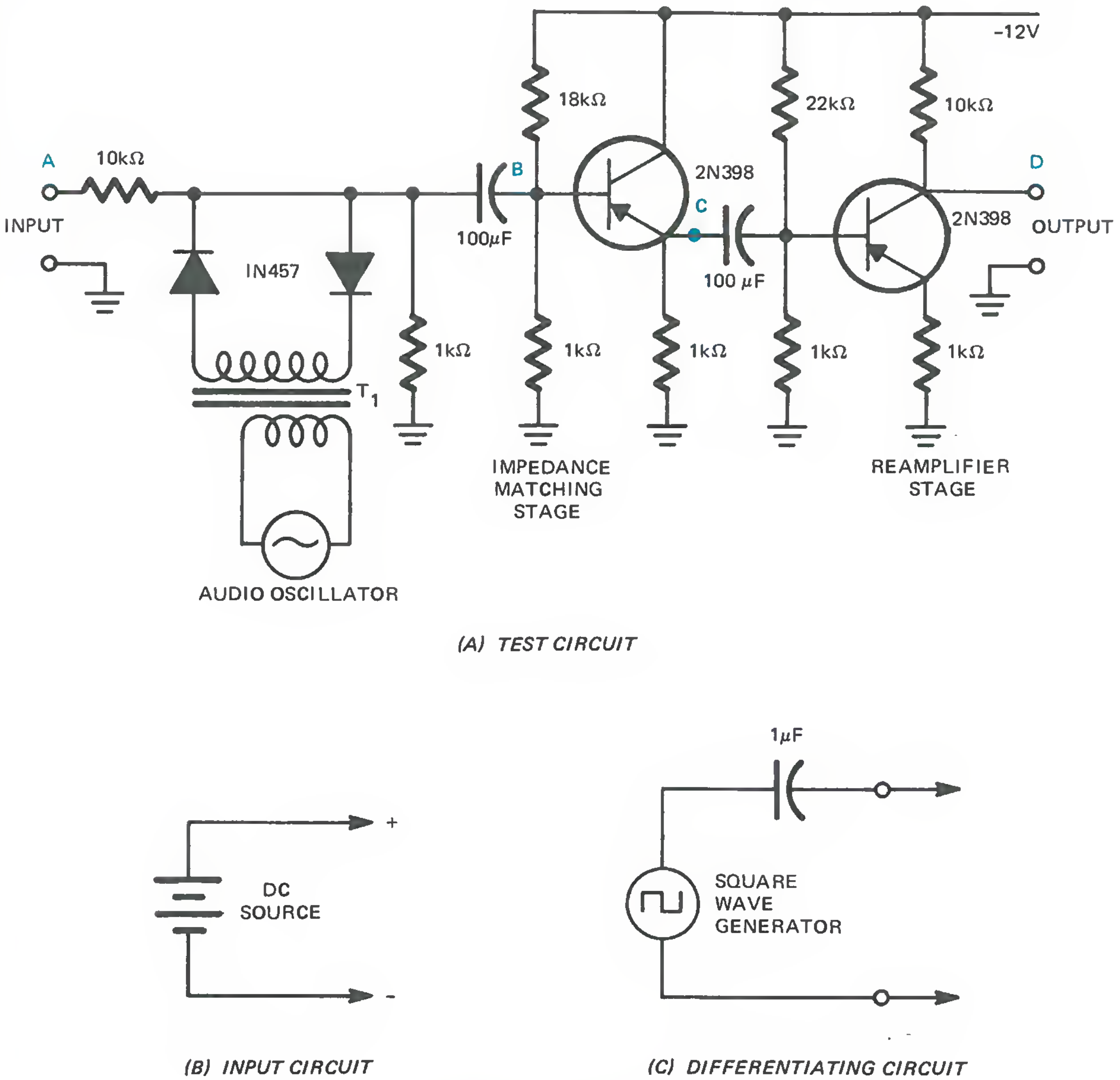


Fig. 5-12 Test Setup

4. Measure and record the voltage and waveforms at points A, B, C and D.
5. Repeat steps 3 and 4 for DC input voltages of 1.0, 0.5, 0.0, -0.5, -1.5, and -2.0 volts.
6. Calculate and record the gain of the impedance matching stage using the equation,

$$A_o = \frac{e_o}{e_{in}}$$

7. Calculate and record the gain of the preamplifier.
8. Calculate and record the gain of the entire system.

9. Connect the differentiating circuit shown in figure 5-12C to the input of the electronic chopper.
10. Adjust the frequency of the square wave generator to 20 Hertz and the output voltage to 2 volts peak.
11. Measure and record the voltage and waveforms at points A, B, C and D.
12. Repeat steps 6, 7 and 8.

Input Voltage	+2 DC	+1 DC	+0.5 DC	0 DC	-0.5 DC	-1.5 DC	-2 DC	+2 PK
Impedance Matching Stage Gain								
Preamplifier Stage Gain								
System Gain								

Fig. 5-13 The Data Table

ANALYSIS GUIDE. How can a DC error signal from a transducer be amplified? What is the purpose of the electronic chopper? How does the electronic chopper operate? Why is an impedance matching stage utilized? Why is the gain of the impedance matching stage different from a conventional amplifier?

PROBLEMS

1. The input error signal to an AC amplifier is 0.2 volts. If the output voltage is 10 volts, what is the gain of the amplifier?
2. The AC amplifier in problem 1 has a feedback circuit added that has a feedback ratio of 0.02. Determine the gain of the amplifier circuit.
3. Without feedback, the AC amplifier in problem 1 has an input resistance of 1.5 kilohms. Using the feedback factor in problem 2, what is the input resistance of the amplifier?
4. The amplifier circuit in figure 5-7 has the following components: $R_1 = 10k\Omega$, $R_f = 20k\Omega$ and an input signal, e_{in}, of 1 volt. Calculate the output voltage.
5. The amplifier circuit in figure 5-10 has the following components: R_1 = 1 megohm, C = 0.5 μF and an input signal, $e_{in} = 2 \sin \omega t$. Determine the output voltage equation.
6. The amplifier circuit in figure 5-9 has the following components: R_1 = 1 megohm, C = 0.5 μF and an input square wave voltage with an amplitude of 10 volts and a time duration of 1 second. Sketch the output voltage waveform versus time.

Procedure step 4: (DC input = + 2V)

A TO GROUND

B TO GROUND

C TO GROUND

D TO GROUND

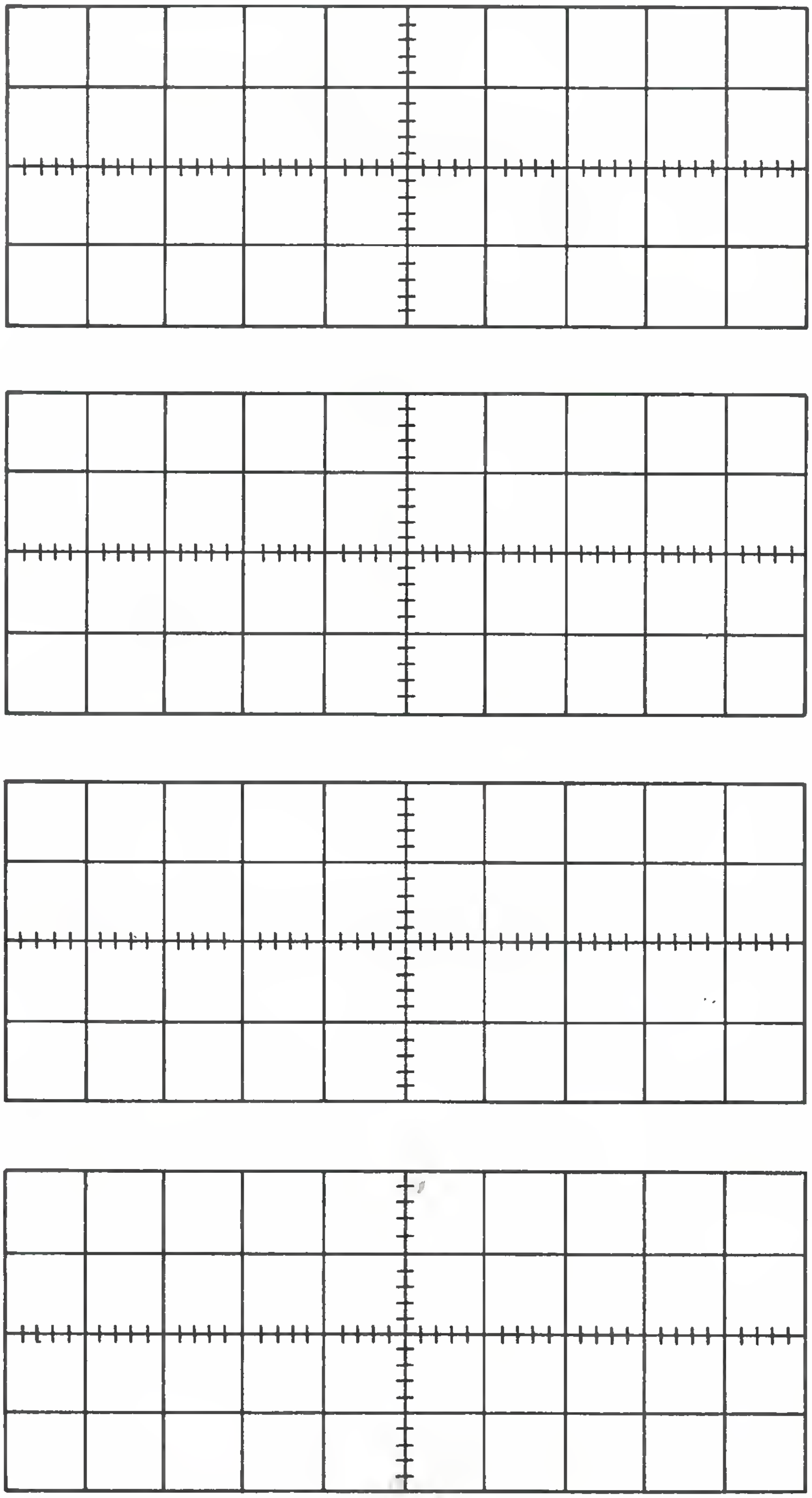
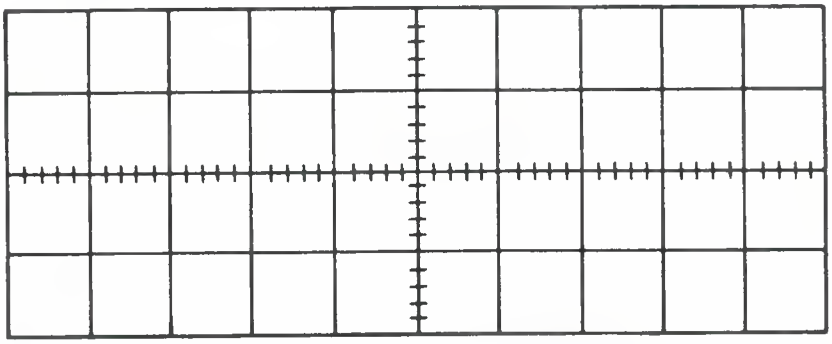


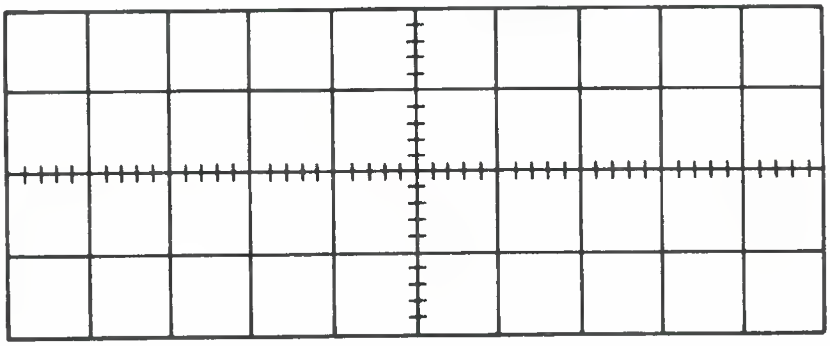
Fig. 5-14 The Results

Procedure step 5: (DC input of 1.0V)

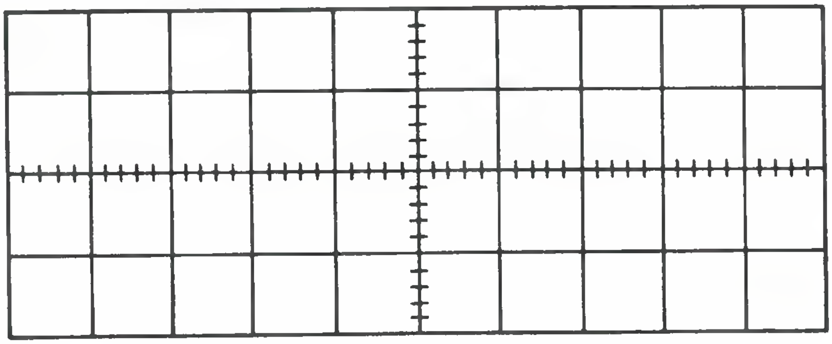
A TO GROUND



B TO GROUND



C TO GROUND



D TO GROUND

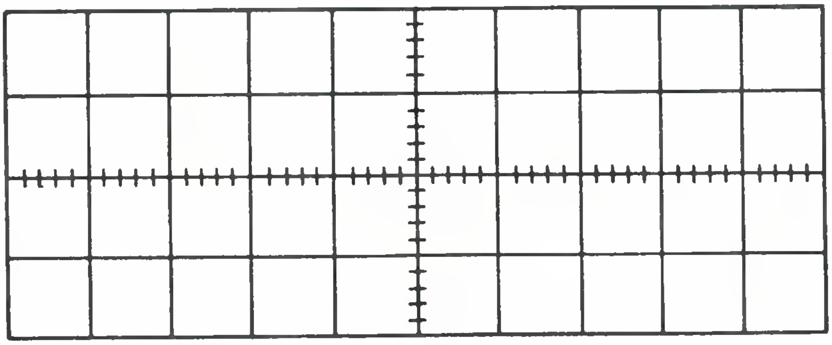
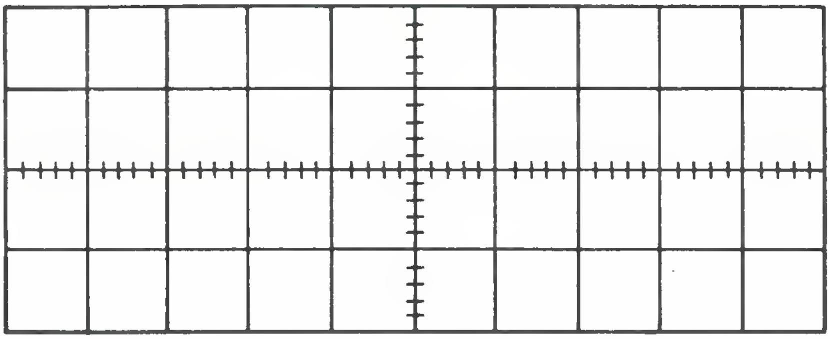


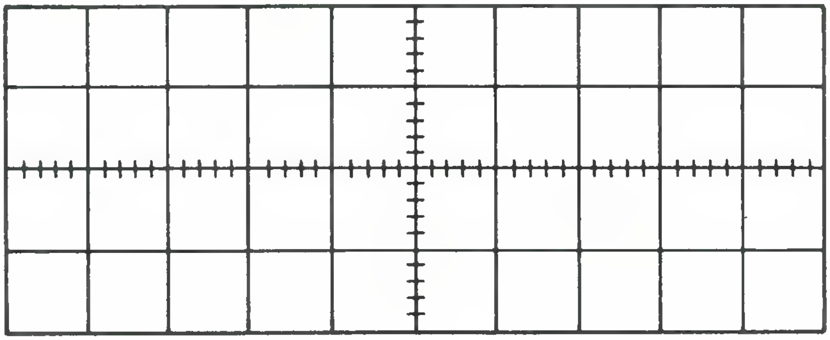
Fig. 5-14 The Results (Cont'd)

Procedure step 5: (DC input = 0.5V)

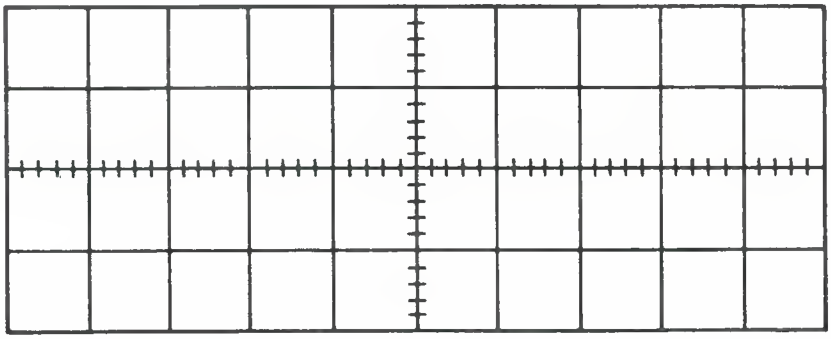
A TO GROUND



B TO GROUND



C TO GROUND



D TO GROUND

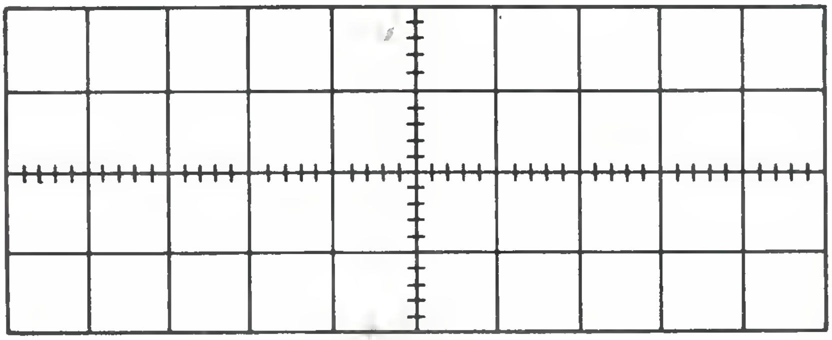
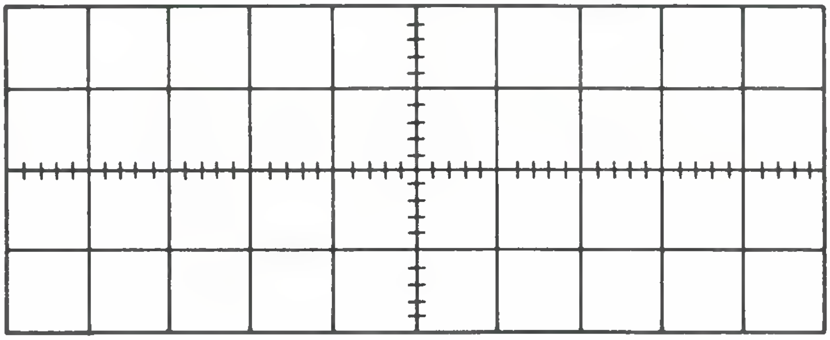


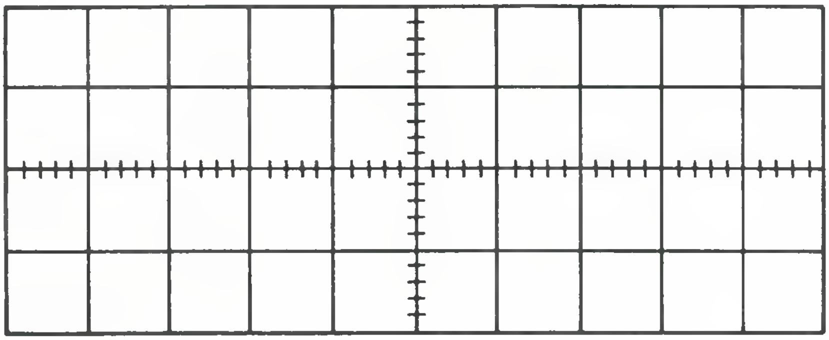
Fig. 5-14 The Results (Cont'd)

Procedure step 5: (DC input = 0V)

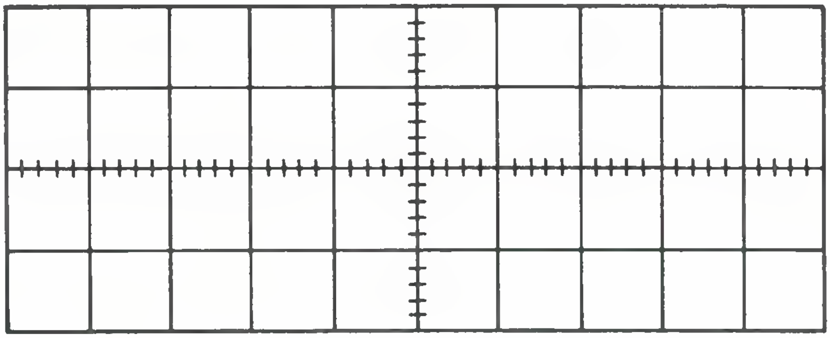
A TO GROUND



B TO GROUND



C TO GROUND



D TO GROUND

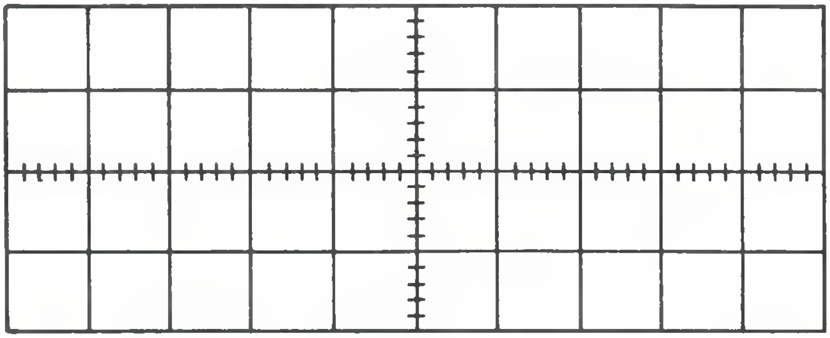


Fig. 5-14 The Results (Cont'd)

Procedure step 5: (DC input = -0.5V)

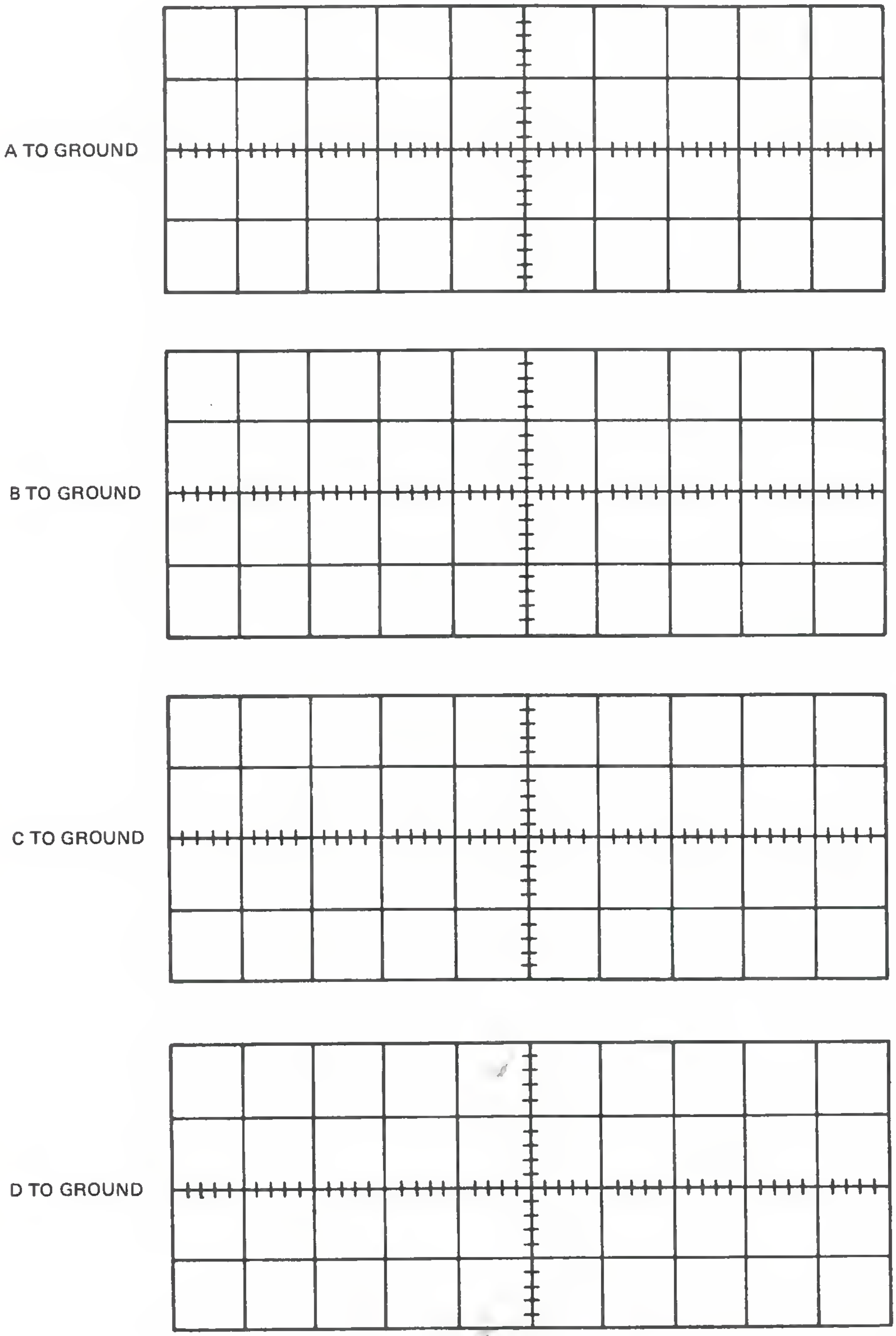
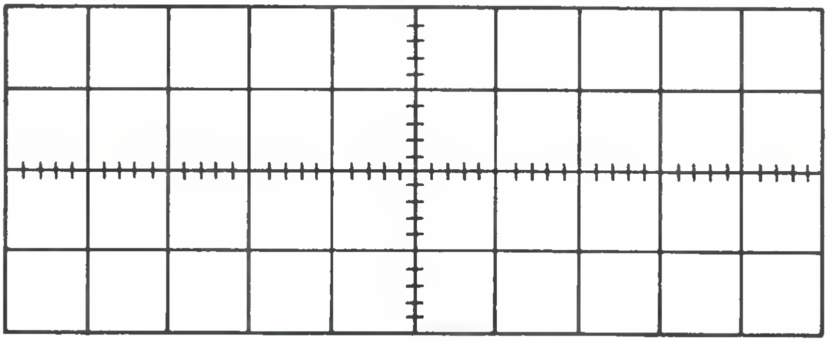


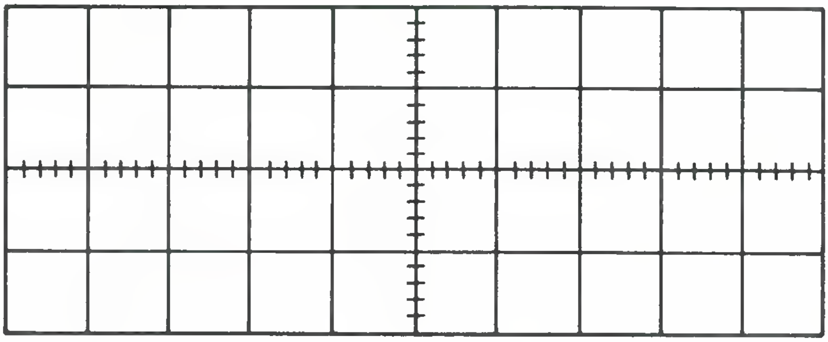
Fig. 5-14 The Results (Cont'd)

Procedure step 5: (DC input = –1.5V)

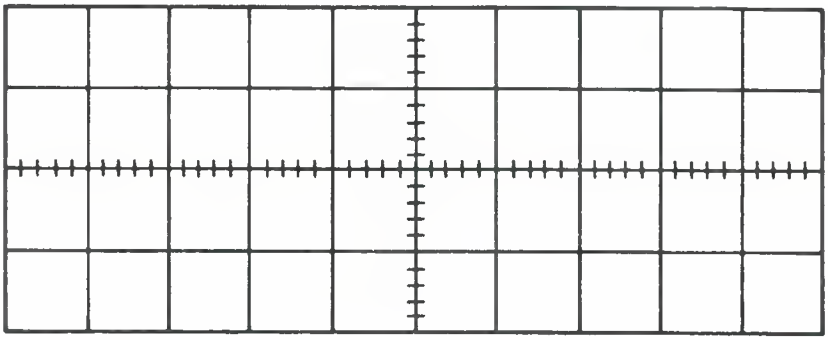
A TO GROUND



B TO GROUND



C TO GROUND



D TO GROUND

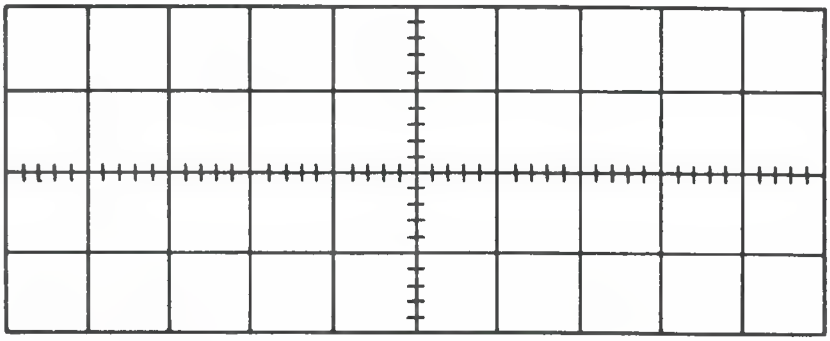
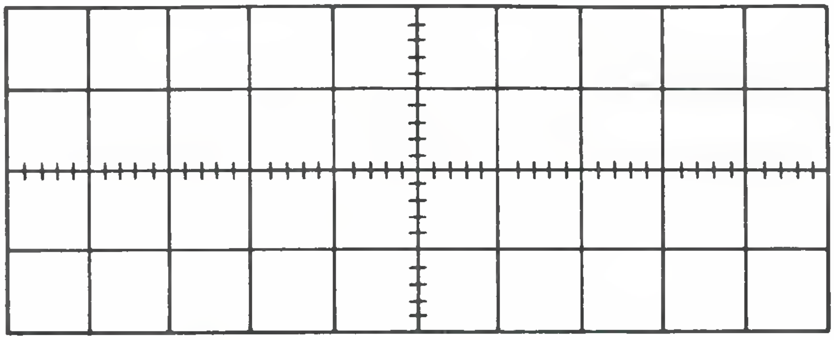


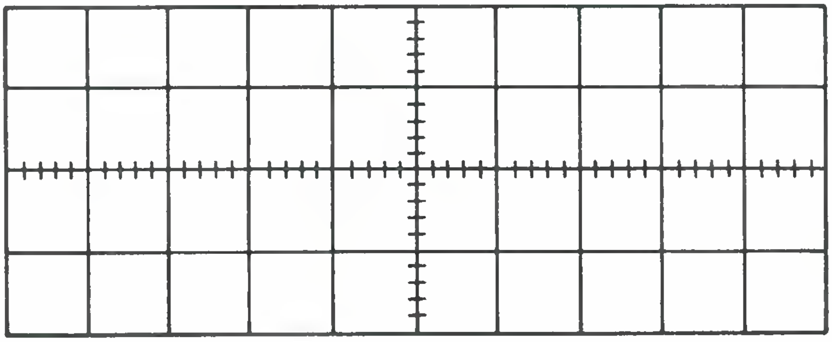
Fig. 5-14 The Results (Cont'd)

Procedure step 5: (DC input = –2.0V)

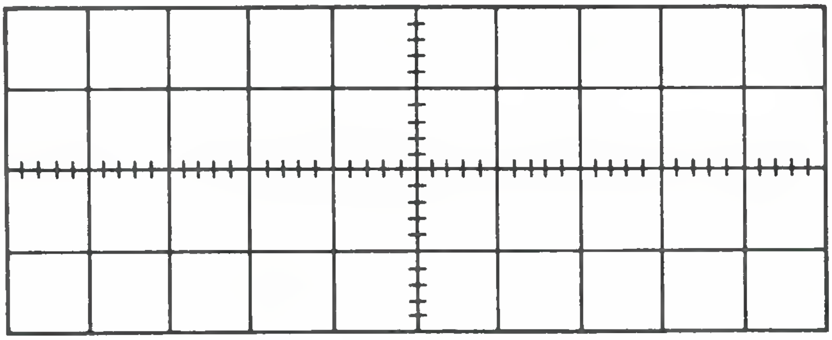
A TO GROUND



B TO GROUND



C TO GROUND



D TO GROUND

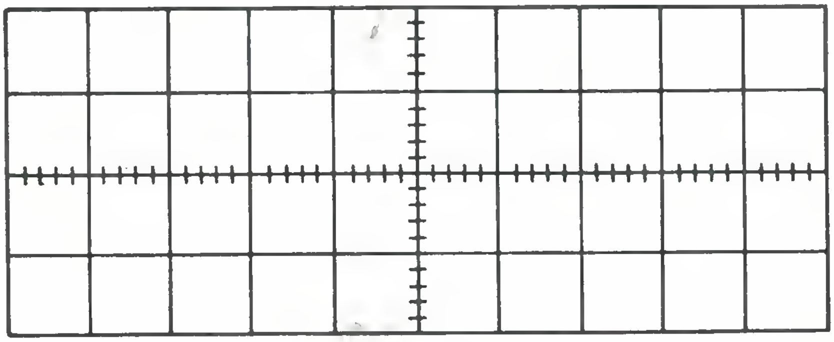
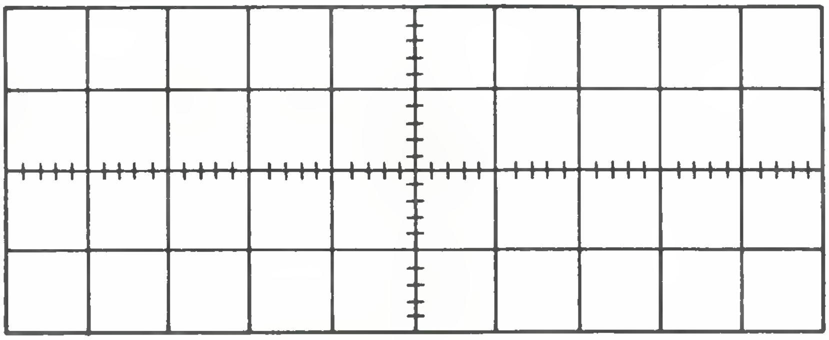


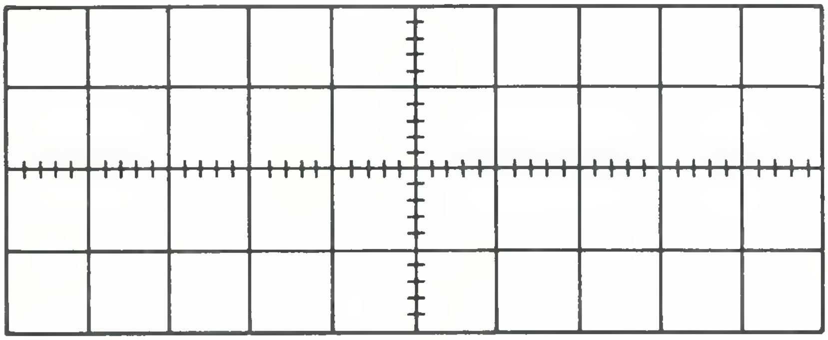
Fig. 5-14   The Results (Cont'd)

Procedure step 11: (AC input = 2 volts peak at 20 Hz)

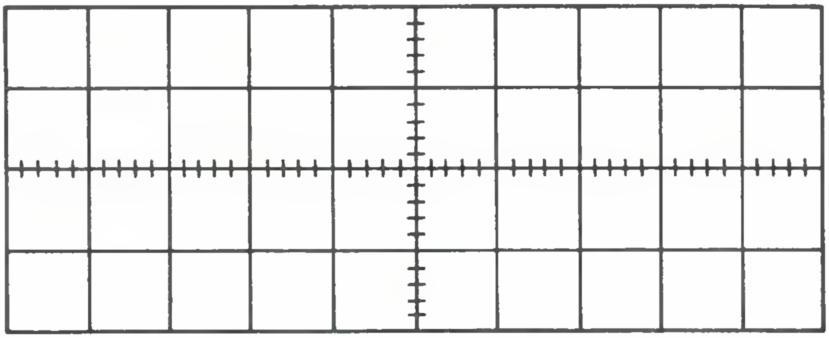
A TO GROUND



B TO GROUND



C TO GROUND



D TO GROUND

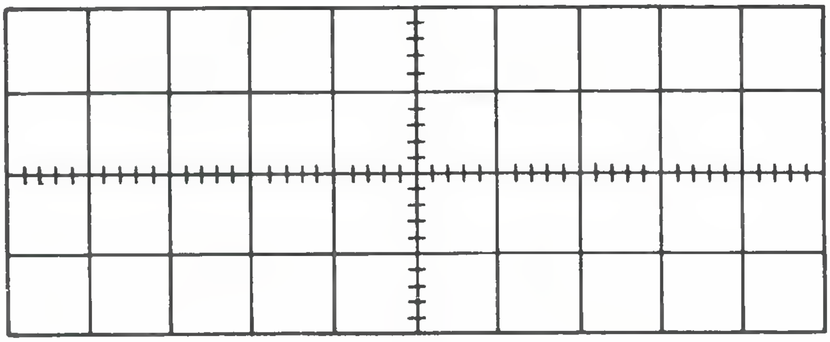


Fig. 5-14 The Results (Cont'd)

experiment 6 PNEUMATIC CONTROLLERS

INTRODUCTION. A large number of controllers use compressed air as the control medium. In the presence of explosive or inflammable vapors, pneumatic systems are safer than electronic ones. In this experiment a pneumatic controller will be examined.

DISCUSSION. Pneumatically-operated controllers for automatic control systems are simple and require very little maintenance. The system provides high power amplification using small amounts of compressed air.

A simple two-step controller is shown in figure 6-1. The system utilizes a combination flapper and nozzle mechanism and a pneumatic relay. The mode of operation is as follows. If the controlled variable is greater than the desired value, the output of the transducer causes the flapper to move toward the nozzle. This causes an increase of pressure at the nozzle, allowing the bellows to expand, opening the poppet valve. Opening the poppet valve allows more air to escape to the atmosphere, reducing the output pressure.

If the controlled variable is less than the desired value, the output of the transducer causes the flapper to move away from the nozzle. This causes a decrease of pressure at the nozzle, allowing the bellows to collapse,

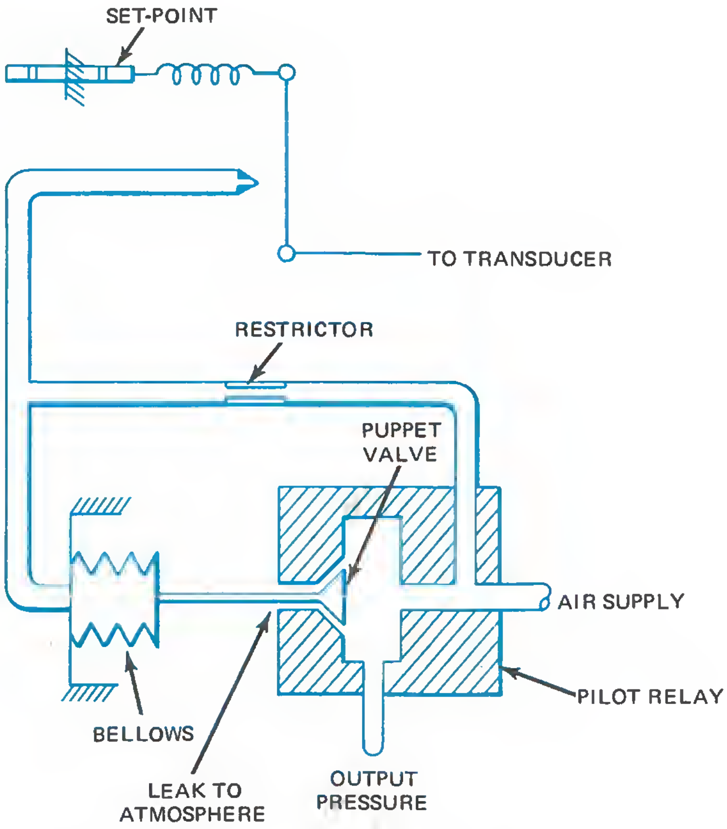
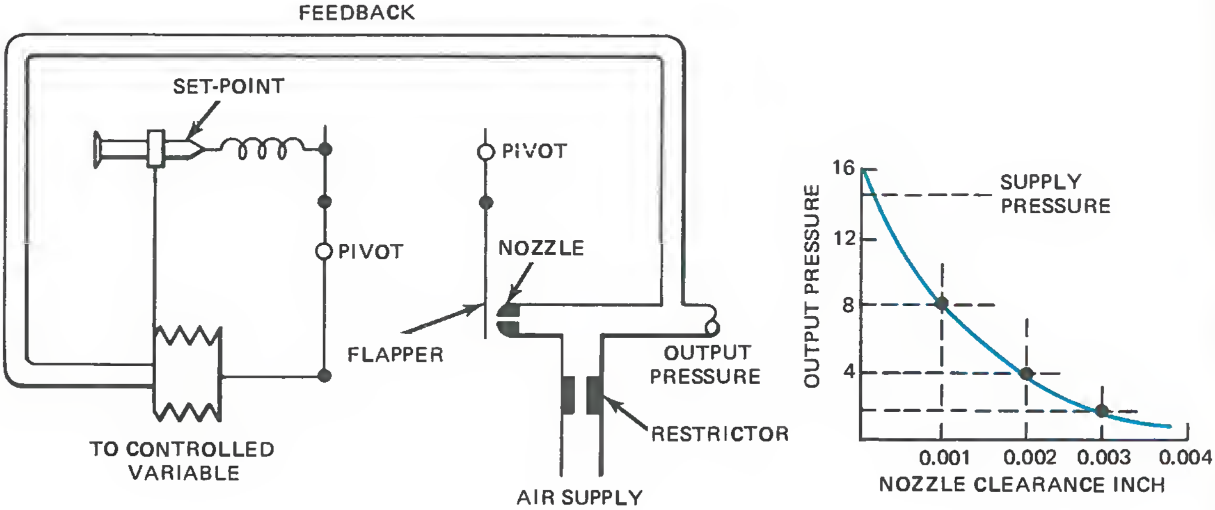


Fig. 6-1 Pneumatic On-Off Controller



(A) FLAPPER & NOZZLE AMPLIFIER *(B) FLAPPER-NOZZLE CHARACTERISTICS*

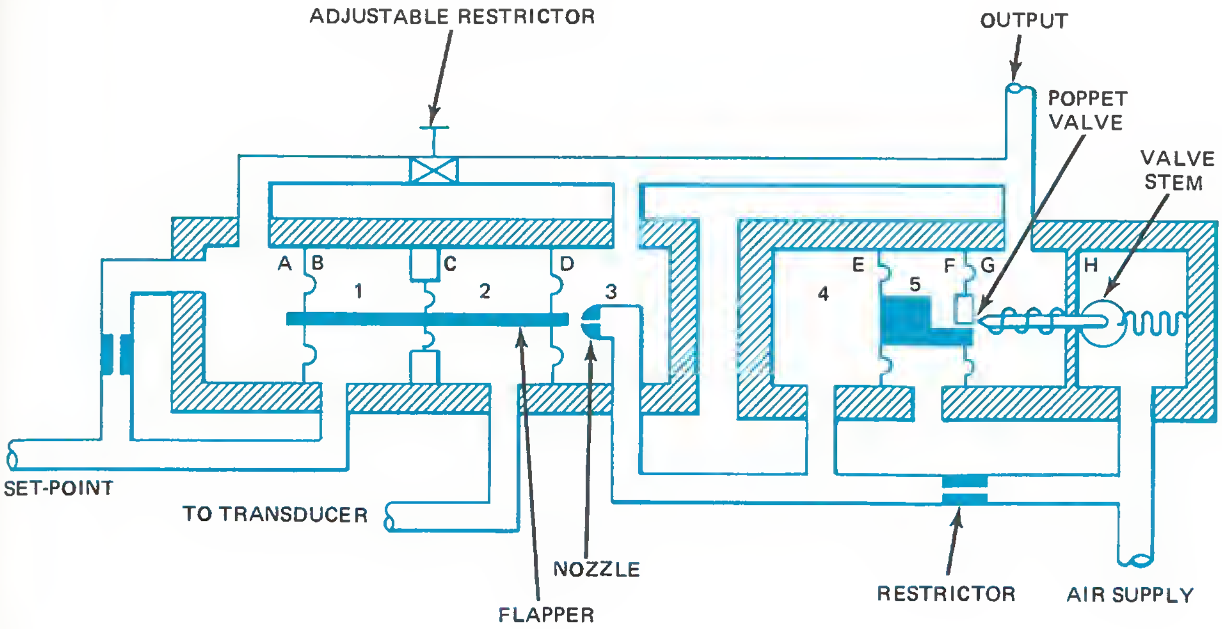
Fig. 6-2 The Flapper-Nozzle Amplifier

closing the poppet valve. Closing the poppet valve reduces the amount of air escaping to the atmosphere, increasing the output pressure. A full change of output pressure is obtained for a very small movement of the flapper. The relay system is a proportional system with a very narrow proportional band; hence, it can be used as a two-step controller.

The flapper-nozzle combination in various forms is the basis of most pneumatic controllers. A simple flapper-nozzle amplifier is shown in figure 6–2A.

Air at a constant pressure is supplied to the nozzle through a restrictor, which has a diameter of about 0.010 inch. The nozzle has a diameter of about 0.020 inches. A flapper is positioned against the nozzle opening in accordance with the transducer output and the set-point. The nozzle back pressure is inversely proportional to the distance between the nozzle opening and the flapper. A flapper motion of about 0.002 inch is sufficient to provide the full range of output. The output pressure of the device is related to the flapper-nozzle clearance by the curve in 6–2B. The proportional sensitivity can be adjusted by moving the flapper pivot point.

The flapper-nozzle amplifier shown in figure 6–2 can be used as a proportional type controller. The operation is as follows: When the controlled variable (output pressure) increases, the bellows expand, moving the flapper away from the nozzle, allowing more air to be vented to the atmosphere. This action reduces the output pressure to the set-point value. A decrease in output pressure causes the bellows to collapse, moving the flapper toward the nozzle, reducing the amount of air vented to the atmosphere. This action increases the output pressure to the set-point value. The proportional sensitivity and the displacement amplification is very high (1000 to 1). The flapper-nozzle amplifier is classified as a displacement type.



A – POSITIVE FEEDBACK CHAMBER
B – SET-POINT CHAMBER
C – TRANSDUCER INPUT CHAMBER
D – NEGATIVE FEEDBACK CHAMBER

E – NOZZLE-BACK PRESSURE CHAMBER
F – EXHAUST CHAMBER
G – OUTPUT PRESSURE CHAMBER
H – SUPPLY CHAMBER

Fig. 6-3 Proportional Force Type Controller

A force-type proportional controller is shown in figure 6–3. The force type controller operates by converting the controlled variable and set-point into corresponding forces. This type controller provides greater flexibility in achieving various kinds of control action.

The set-point pressure signal, which is usually supplied by a pressure regulator, is applied to the set-point chamber (B). The pressure in the positive feedback chamber (A) exerts a force to the right on diaphragm 1. The pressure in the negative feedback chamber (D) exerts a force to the left on diagraphm 3. The two forces are balanced since both chambers obtain their pressure from the same source, the output pressure chamber. Thus, if the set-point pressure and the transducer input pressure are equal, the entire section is balanced and the flapper is stationary.

If the pressure from the transducer increases as a result of an increase in the value of the process variable, the increased pressure exerts a force to the left on diaphragm 2 and to the right on diaphragm 3. Diaphragm 3 has twice the area as diaphragm 2 and the result is a movement of the flapper to the right. This movement reduces the clearance between the flapper and nozzle, increasing the pressure in the nozzle back-pressure chamber (E). The increased pressure in the nozzle back-pressure chamber forces diaphragms 4 and 5 to the right against the action of the spring. This action closes the poppet valve and forces the valve stem to the right, thus opening the supply port and permitting air to enter the output

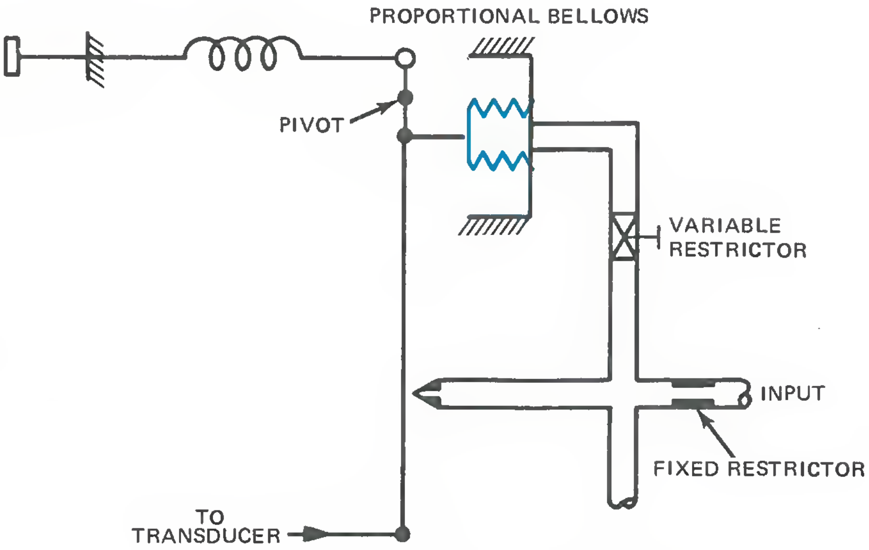


Fig. 6-4 Proportional Plus Derivative Control

pressure chamber (G). The pressure in the output chamber increases and exerts a force to the left on diaphragm 5. Since the negative feedback chamber is directly coupled to the output pressure chamber, its pressure increases and exerts a force to the left on diaphragm 3. The pressure continues to increase until (1) the force to the right and the force to left on diaphragm 3 are equal and (2) the force to the right and the force to the left on diaphragm 5 are equal. At this point the valve stem returns to its original position with the supply of air to the output-pressure chamber shut off. The pressure exerted by the output will vary in direct relationship with the transducer input. For any given output signal, the pressure in the positive feedback chamber will depend on the ratio between the fixed orifice restriction and the adjustable orifice restriction. With the adjustable restriction fully closed, there is no positive feedback from the output, and the proportional band is very wide. With the adjustable restriction fully opened, there is positive feedback and the proportional band is at its narrowest.

A proportional-derivative controller is shown in figure 6–4. The addition of the variable restrictor results in a delayed negative feedback. If the controlled variable suddenly changes value, the transducer will cause the flapper to step further open or closed. The direction of change will be determined by the direction of the change in the controlled variable. The change in flapper positions will cause the output pressure to change suddenly, but the pressure in the bellows can only change slowly. The slower pressure change in the bellows is due to the variable restrictors and the capacity of the bellows. This delays and reduces the feedback, and, since the feedback is negative, the output pressure is higher and leads the transducer signal. Thus, the delayed negative feedback produces a derivative response.

The derivative time is the product of the resistance of the feedback restriction and the capacitance of the bellows. Therefore, adjustment of the restriction adjusts the derivative time.

A proportional-integral controller is essentially a proportional controller with a posi-

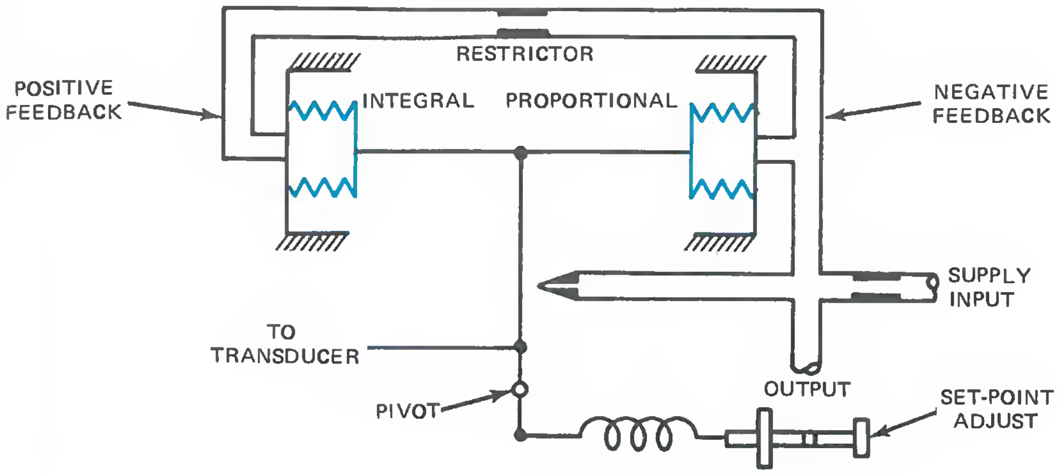


Fig. 6-5 Proportional Plus Integral Control

tive feedback and a restrictor. When the transducer input suddenly increases, the flapper-to-nozzle clearance decreases and the output pressure increases. The output pressure is applied directly to the negative feedback bellows, which repositions the flapper and stabilizes the output pressure at a new value. But, the pressure in the positive feedback bellows commences to change. This change in pressure will be proportional to the duration of the deviation since the bellows acts as a capacitance which is charged through a variable restrictor. Thus, the rate of change of the pressure in the bellows is proportional to the pressure difference across the restrictor and the capacitance of the bellows. This action will cause the flapper to be moved closer to the nozzle as the integral bellows lengthens and will further increase the output pressure. The above action continues until the pressure in the two bellows is equal and the controlled variable returns to its desired value. The proportional sensitivity is adjusted by selecting the position of the pivot, and the integral time is adjusted by the value of the restrictor in the positive feedback line.

The optimum controller combines proportional, integral and derivative control action. This type of controller is termed a proportional-plus-reset-plus-rate controller. The method of obtaining the three actions is shown in figure 6-6.

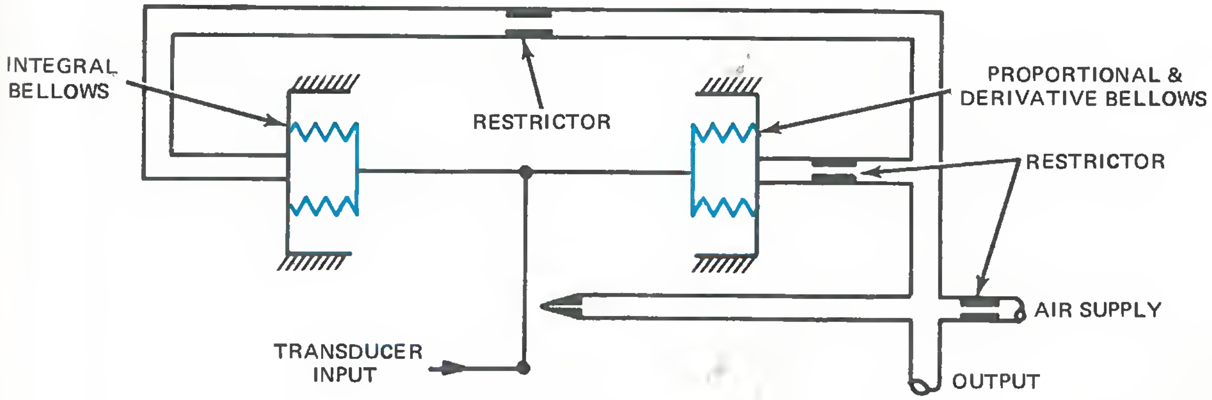


Fig. 6-6 Proportional-Plus Reset-Plus Rate Controller

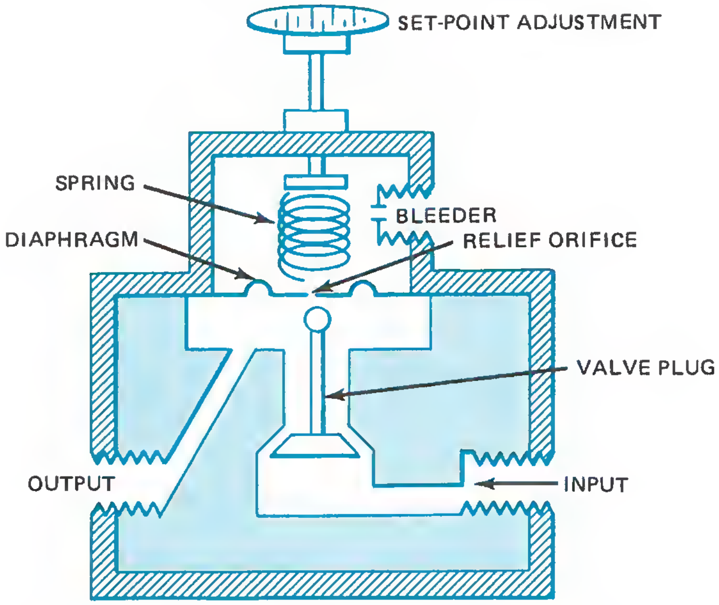


Fig. 6-7 Self-Operated Controller

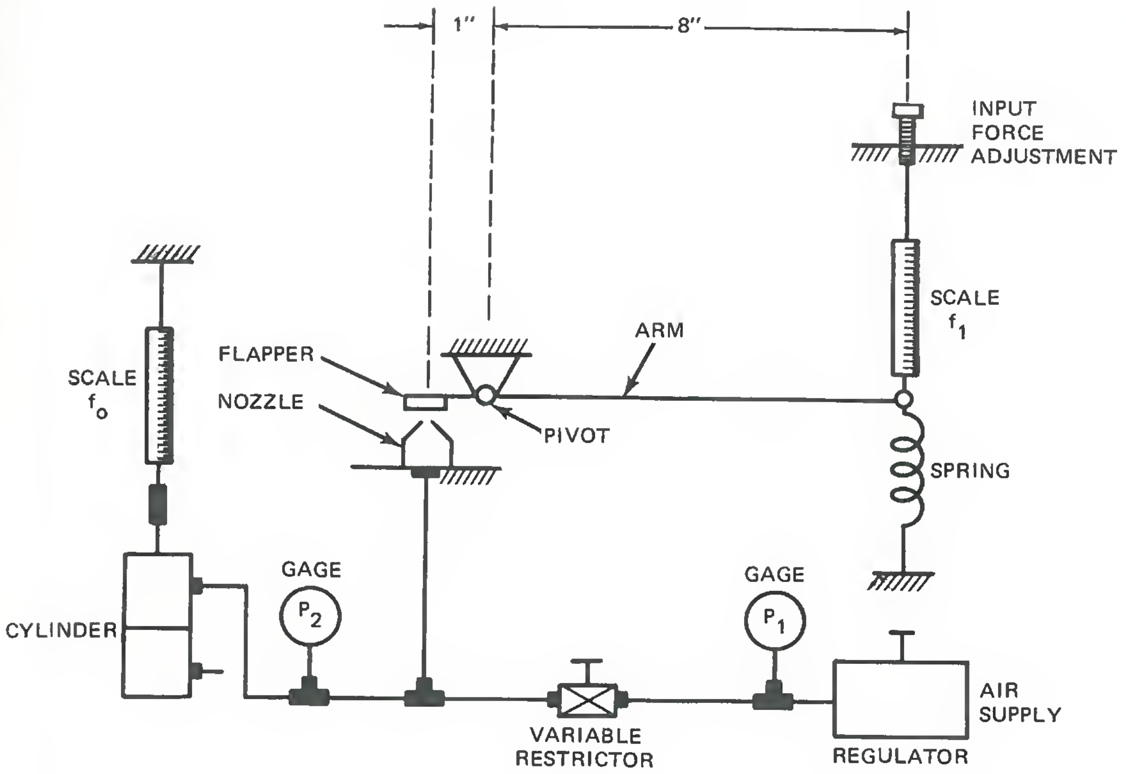
A self-operated controller, usually termed a pressure regulator, is shown in figure 6-7. The regulator is a dead-end (contains a relief valve) type. The set-point is determined by the adjustment of the spring compression. The diaphragm measures the output pressure, and the sensor is the force acting on the valve plug. The manipulated variable is the flow rate past the valve plug, and the controlled variable is the output pressure. When the output pressure is low the diaphragm moves downward because the spring force is greater than the upward force, due to the pressure acting against the area of the diaphragm. The movement stops when the force upward is equal to the force downward. This action increases the flow of air and raises the output pressure. When the output pressure is high, the valve plug reduces the flow of air and lowers the output pressure.

MATERIALS

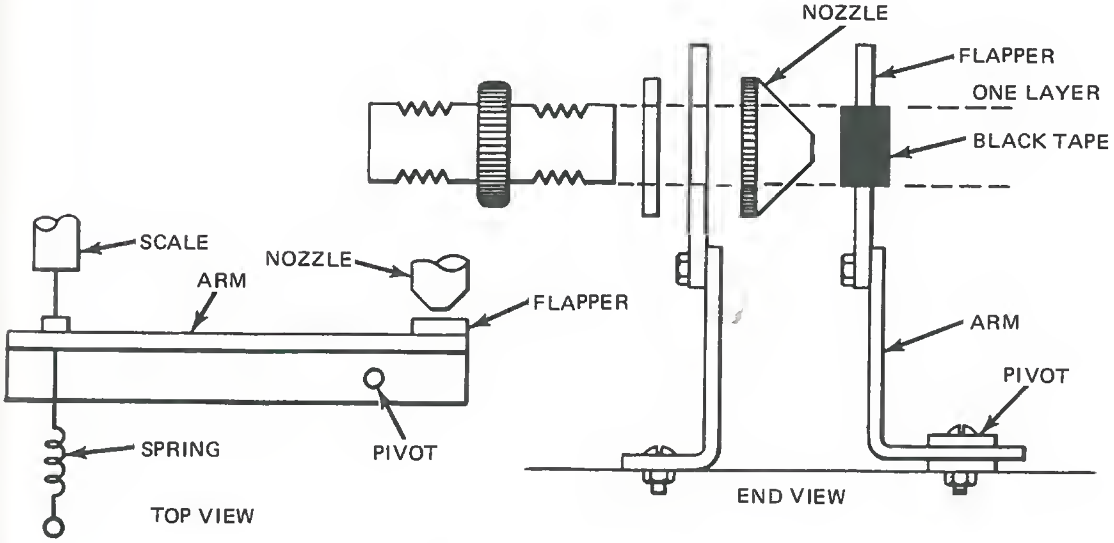
1 Spring, approximately 1/8 in. dia. X 3/4 in. long
2 Pressure gages 0–30 psi
1 Spring balance, 0–3000 grams
1 Spring balance, 0–1000 grams
1 Air cylinder, 1 in. dia. X 4 in. stroke
1 Manual shut-off valve
1 Air-regulated supply, 0–30 psi
1 Copper flare nut, 0.25 in. ID
1 Copper adapter fitting, 0.25 in. ID flare to 0.25 in. NPT
3 Copper T-type fitting
1 Flapper arm 9 in.
Miscellaneous nuts, bolts and tubing

PROCEDURE

1. Construct the experimental set-up shown in figure 6-8.



(A) Schematic



(b) Flapper and Nozzle Assembly

Fig. 6-8 Pneumatic Amplifier Test Setup

2. Adjust the regulator to 15 psi (P_1).
3. With the nozzle completely closed by the flapper, adjust variable restrictor until the output force (f_o) is 2500 grams. **Do not change the setting of the variable restrictor for the remainder of the experiment.**
4. Decrease the input force adjustment until the force output is zero grams.
5. Read and record the force input in the Data Table as f_x.
6. Increase the input force by 25 grams.
7. Read and record the input force (f_1), the output force (f_{out}) and the pressure, P_2.
8. Calculate and record the amplifier input force (f_{in}) by

$$f_{in} = f_1 - f_x$$

9. Repeat steps 6 and 7 in 25 gram increments until the output force is 2500 grams.
10. Calculate and record the force gain (A_f) of the amplifier by using

$$A_f = \frac{f_{out}}{f_{in}}$$

f_x	f_1	f_{in}	f_{out}	A_f	P_1	P_2
		0 grams	0 grams	0	15 psi	0
					15 psi	
					15 psi	
					15 psi	
					15 psi	
					15 psi	
					15 psi	
					15 psi	
					15 psi	
					15 psi	

Fig. 6-9 The Data Table

ANALYSIS GUIDE. Plot a graph of force input versus force output. Plot a graph of pressure output versus force output. Discuss the relationship of the amplifier gain with output pressure and force.

PROBLEMS

1. Draw a diagram showing the addition of negative feedback to the amplifier system in figure 6–8A.
2. Draw a diagram showing the addition of positive feedback to the amplifier system in figure 6–8A.
3. Redesign the amplifier in figure 6–8A to incorporate rate action.
4. Redesign the amplifier in figure 6–8A to incorporate reset action.
5. Draw the electrical analogy to the amplifier in figure 6–8A.

experiment 7 HYDRAULIC CONTROLLERS

INTRODUCTION. Hydraulically-operated controllers provide great power and positiveness of action. In this experiment we will examine some of the characteristics of this type of controller.

DISCUSSION. Essentially, a hydraulic controller is a fulid system that is closed. A pneumatic system can be vented to the atmosphere, but a hydraulic system employs a sump that collects the return fluid from the system and serves to dissipate heat. Since the motor and pump run continuously, it may be necessary to employ an oil cooler as heat causes the viscosity of the fluid to change. An accumulator can be connected to the outlet side of the pump to serve as a reservoir of high pressure fluid. The accumulator contains a diaphragm with one side filled with gas, usually nitrogen, at a pressure of several hundred pounds per square inch. The accumulator can run the system for a short time after the electric motor stops. The system must be well filtered to insure satisfactory operation. A relief valve is used to prevent the system from exceeding a given operating value. A hydraulic supply system is shown in figure 7-1.

The two principal methods of operation of hydraulic controllers are the jet-pipe control and the four-way valve control. In both cases, the input to the controller must be a mechanical force to position memeber in the controller. Also, a steady supply of hydraulic

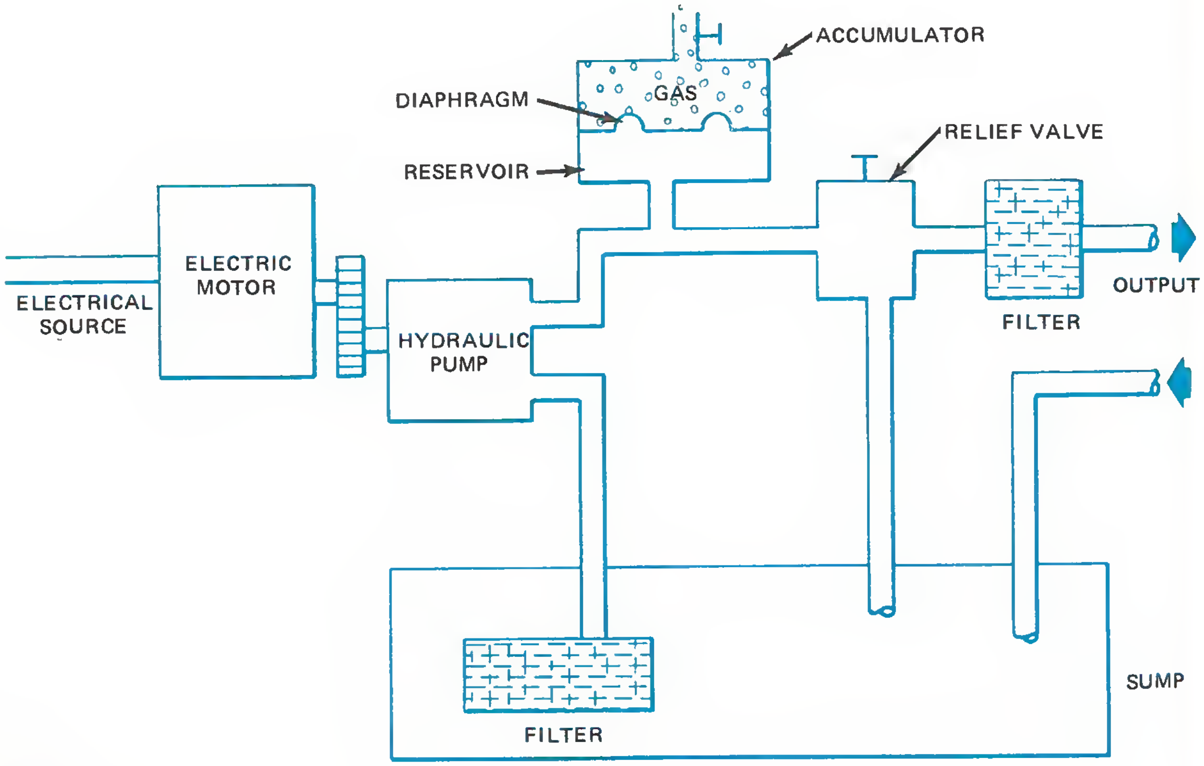


Fig. 7-1 Hydraulic Supply System

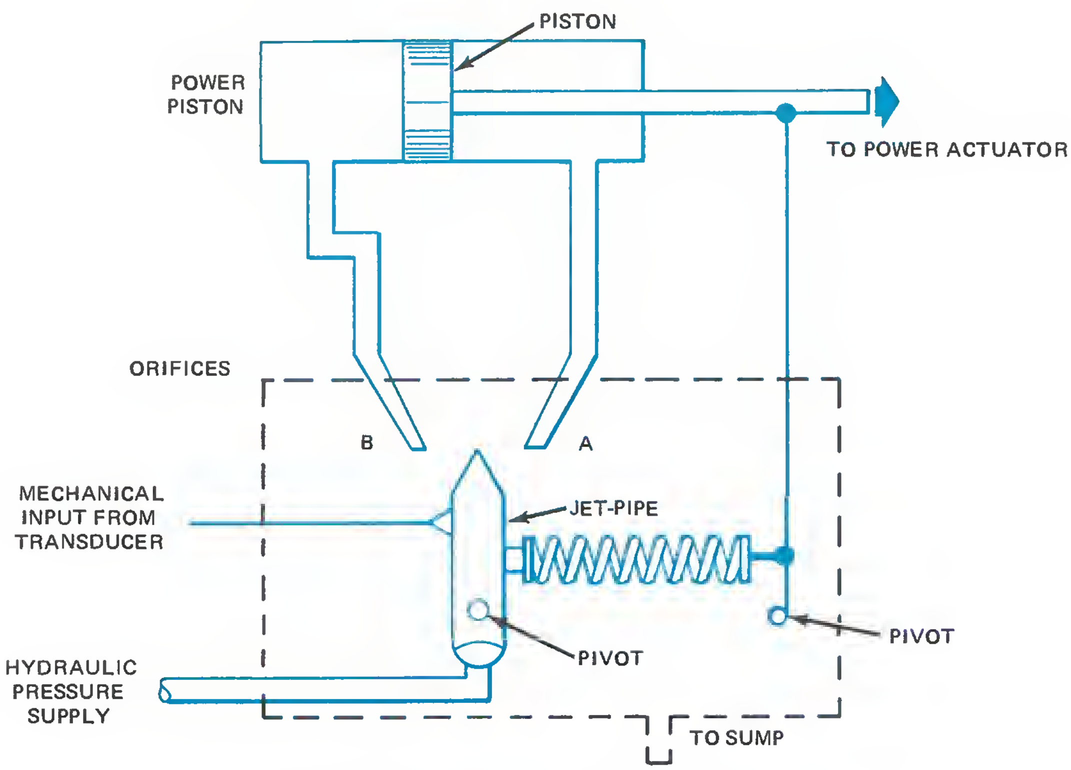


Fig. 7-2 Jet-Pipe Hydraulic Controller with Proportional Controls

fluid under pressure must be used. Hydraulic controllers providing proportional, rate or reset action or any combination of the three responses are readily available.

A proportional hydraulic controller utilizing jet-pipe control is shown in figure 7-2. High pressure hydraulic fluid is pumped through the jet-pipe.

The jet-pipe is pivoted to permit it to swing approximately 0.006 inches. When the controlled variable is at the desired value, the mechanical input and the feedback position jet-pipe such that the fluid pressure impinging on orifice A is equal to the fluid pressure impinging on orifice B. The pressure on the right side of the cylinder is equal to the pressure on the left side of the cylinder. Therefore, the piston does not move. If the controlled variable is greater than the desired value, the jet pipe swings to the right and increases the pressure on the right side of the piston while decreasing the pressure on the left side. The piston moves to the left, increasing the feedback force to the left, and returns the jet pipe to a neutral position. This is proportional action. Changing the location of the pivot point on the feedback arm provides a proportional band adjustment.

On-Off, or two position control, is accomplished in the hydraulic controller by a very rapid movement of the piston to its extreme positions when the measured value changes a slight amount from the set-point.

Proportional plus integral action can be accomplished with the addition of an auxiliary

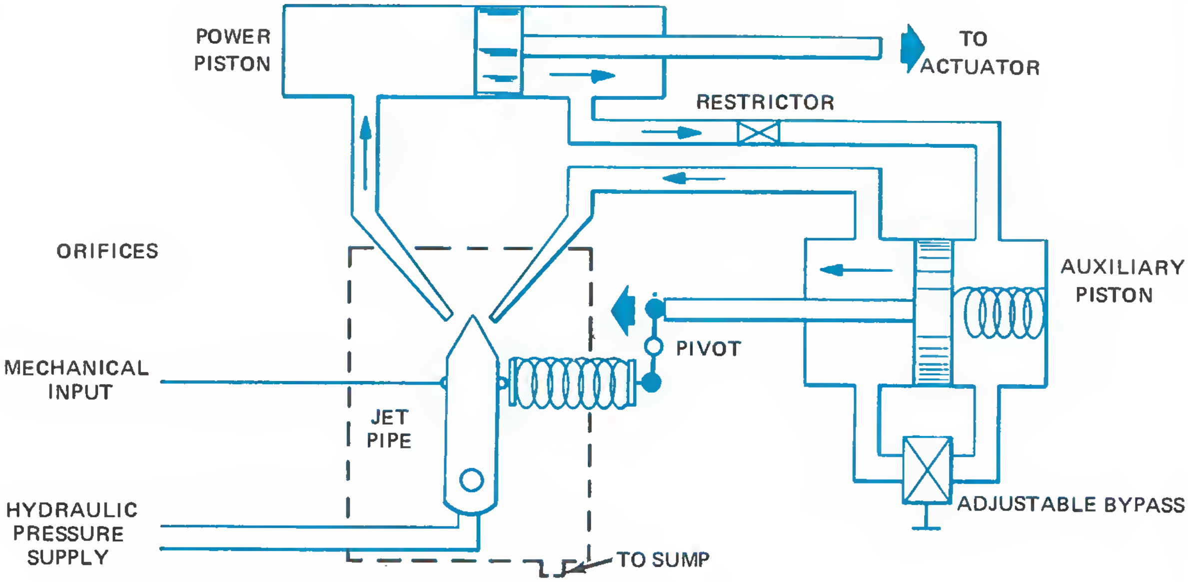


Fig. 7-3 Jet-Pipe Hydraulic Controller with Proportional Plus Integral Control

piston with an adjustable bypass. This system is shown in figure 7-3. If the controlled variable is greater than the desired value, the jet pipe swings to the left and increases the pressure on the left side of the power piston, thus decreasing the pressure on the left side of the auxiliary piston. The power piston moves to the right and causes fluid to flow into the right side of the auxiliary piston. The auxiliary piston moves to the left, increases the force on the feedback arm and returns the jet pipe to a neutral position. The foregoing action is proportional. However, the pressure difference across the auxiliary piston causes fluid to flow through the restrictor and allows the auxiliary piston to move to the right. This causes the jet pipe to move to the left. This again causes the power piston to move to the right. This continuing action depends upon the time integral of the input mechanical signal and is an integral action. The proportional sensitivity can be adjusted by moving the pivot point on the feedback arm. The integral time is adjusted by the bypass valve.

A simple one-tube hydraulic controller is shown in figure 7-4. If the controlled variable

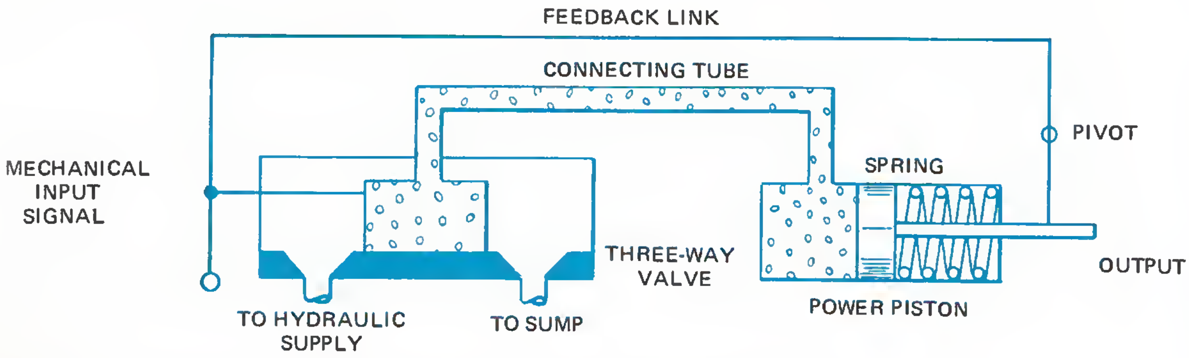


Fig. 7-4 A One-Tube Hydraulic Controller

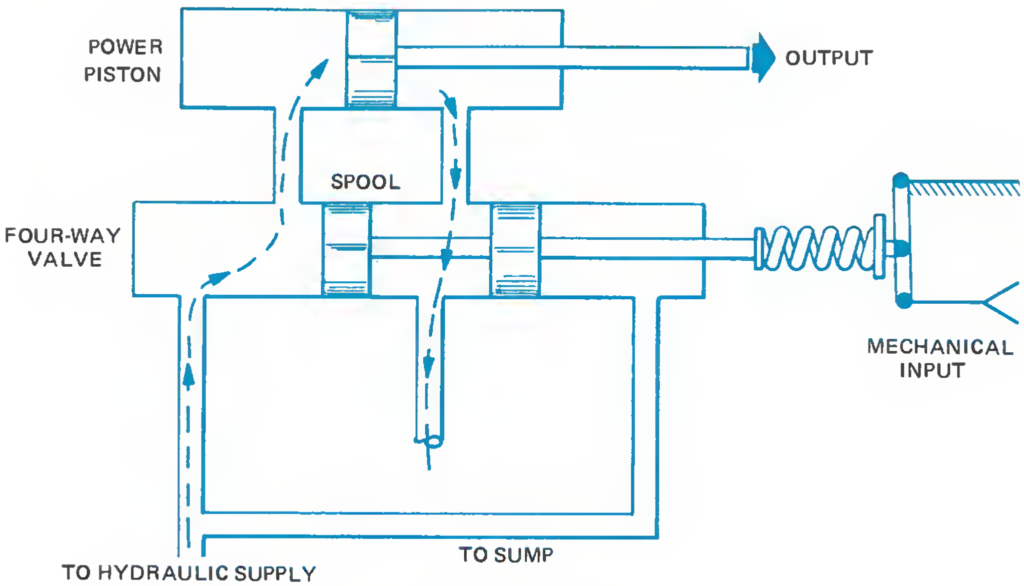


Fig. 7-5 Four-Way Valve

is greater than the desired value, the mechanical input moves the connecting tube to the right. This opens the connecting tube to the sump, the fluid pressure at the power piston is reduced, and the spring pushes the power piston to the left. The feedback link is connected from the otuput of the power piston to the input of the three-way valve. The feedback moves with the power piston and tends to close the connecting tube. This action continues until the force on the power piston due to the fluid pressure acting to the right and the spring force acting to the left are equal. Thus, the position of the power piston is proportional to the mechanical input signal. One tube hydraulic controllers are usually employed in speed controls for engines.

To obtain a higher power output force than that which can be obtained from the jet-pipe, the four-way valve control is employed. A four-way valve is shown in figure 7-5. If the controlled variable is greater than the desired value, the mechanical signal input moves the spool to the right. Supply fluid flows through the left side of the four-way valve into the left side of the power piston. This causes the power piston to move to the right. As the piston moves to the right, fluid ahead of it is forced out through the drain line into the sump. At the same time, the power piston, connected through a feedback linkage to the spool of the four-way valve, moves the spool to the left until the neutral or balanced position is obtained. When the spool is in the balanced position, the force on the power piston is zero, since fluid flow to the piston is cut off. If the input signal is weak, the four-way valve can be positioned by the use of a jet-pipe ahead of the four-way valve. The action of the jet-pipe controlling the four-way valve is called a booster. The booster system has an increased mechanical advantage.

The hydraulic controller usually consists of two operating units: a pilot valve to control oil pressure and the output flow, and a power piston to provide the required displacement of the final control element or actuator.

MATERIALS

1 Scale, 0–6 inches
2 Springs, spring constant 4 lbs/in., 6 in. length
1 1-lb weight
1 1/2 lb weight
2 2 lb weights
1 5 lb weight
1 2-way cylinder, 1-1/2 in. diameter piston, six-in. stroke
1 4-way valve, electrically-controlled
2 Pulley, 2 in. diameter
1 Hydraulic supply, regulated 0–25 psi
3 Gages, 0–30 psi
2 Switches, SPST momentary ON, 110 volts, 4 amps
Miscellaneous nuts, bolts, etc.

PROCEDURE

1. Construct the test setup shown in figure 7-6.

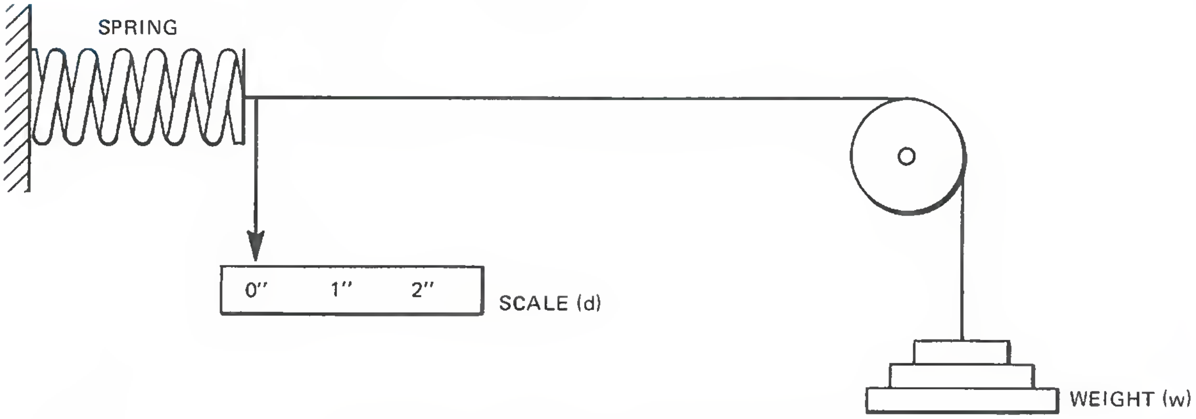


Fig. 7-6 Spring Constant Test Setup I

2. Add weight until the pointer deflects 0.25 inches. Record the weight in the Data Table, figure 7-8, as w.
3. Repeat step 2 in 0.25 inch increments until a two-inch deflection is obtained.
4. Construct the test setup shown in figure 7-7.
5. Adjust the hydraulic supply regulator to 20 psi.
6. Alternately operate S-1 and S-2 until the pointer on the piston rod os the two-way cycle is at the midpoint of its travel.
7. Alternately adjust the spring until the tension in the spring connecting link is taut and the piston rod indicator remains at the midpoint of its travel.
8. Read and record P_2 and P_3 in the Data Table, figure 7-9.
9. Alternately operate S-1 and S-2 until the piston rod pointer indicates +0.5 inches.
10. Read and record P_2 and P_3 in figure 7-9.

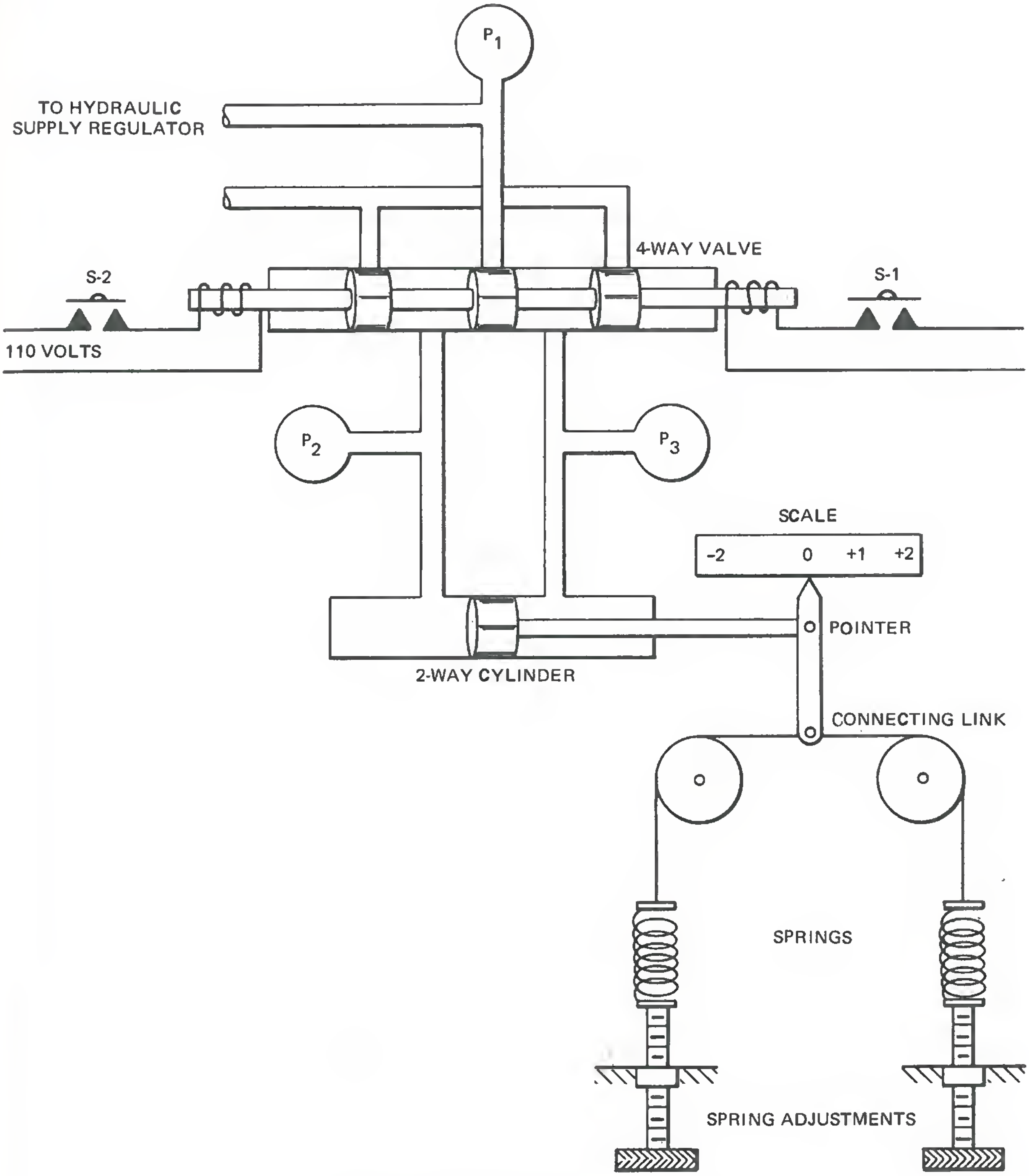


Fig. 7-7 Experimental Setup II

11. Calculate $\Delta P = |P_2 - P_3|$ and record these values in figure 7-9.

12. From the data recorded in the Data Table, figure 7-8, determine the force applied to the spring corresponding to a 0.5 inch deflection. Record this data in the table as F.

d	w
0 inch	0 pounds
0.25	
0.50	
0.75	
1.00	
1.25	
1.50	
1.75	
2.00	

Fig. 7-8 Spring Data

d	P_2	P_3	ΔP	F
0 in.			0 psi	0 lbs
+0.5				
+1.0				
+1.5				
+2.0				
-0.5				
-1.0				
-1.5				
-2.0				

Fig. 7-9 Data Table II 20 psi

13. Repeat steps 9 through 12 for +1.0, +1.5, +2.0, -0.5, -1.0, -1.5, and -2.0 inch piston rod pointer indications.

ANALYSIS GUIDE. Plot a graph of deflection versus force for the spring used in the experiment. Plot a graph of deflection of the piston rod versus force. Plot a graph of ΔP versus F.

PROBLEMS

1. Calculate the force exerted on the spring in figure 7-7 when ΔP is 20 psi and the diameter of the piston is 1-1/2 inches.
2. What force is required to stretch a spring with a spring constant of 10 lbs/inch through a distance of two inches?
3. Discuss the operation of the electrically-operated 4-way valve used in the experiment.
4. Design a hydraulic amplifier using a four-way valve with a mechanically positioned spool and having negative feedback.

experiment 8 ELECTRICAL ACTUATORS

INTRODUCTION. Any process or automatic control system requires a device to correct the controlled variable by varying the manipulated variable. In this experiment, some electrical actuators will be examined.

DISCUSSION. The output of a controller is ultimately applied to an error-correcting device, termed an actuator. The actuator controls the manipulated variable to bring the controlled variable to the desired value. To do this, the actuator must be capable of supplying adequate power and have a good speed response. The actuator's direction of control should be reversible so that it can correct errors in either direction. A servomotor satisfies these requirements. Both DC and AC servomotors are available, the choice being made on the basis of the load power requirements and the nature of the available voltage source.

One form of the DC servomotor used in automatic control is shown in figure 8–1. The split field motor contains two field windings, or what amounts to the same thing, a center-tapped field winding. One field tends to produce armature rotation in one direction and the other field tends to produce rotation in the other direction. For reference, the directions of rotation are identified as clockwise, CW, and counterclockwise, CCW. The armature may be connected independently to the DC supply or through its field windings.

Split field motors are designed to oeprate at relatively low current and may be controlled by SCRs as shown in figure 8–2. If a positive error signal is applied between the terminals 1

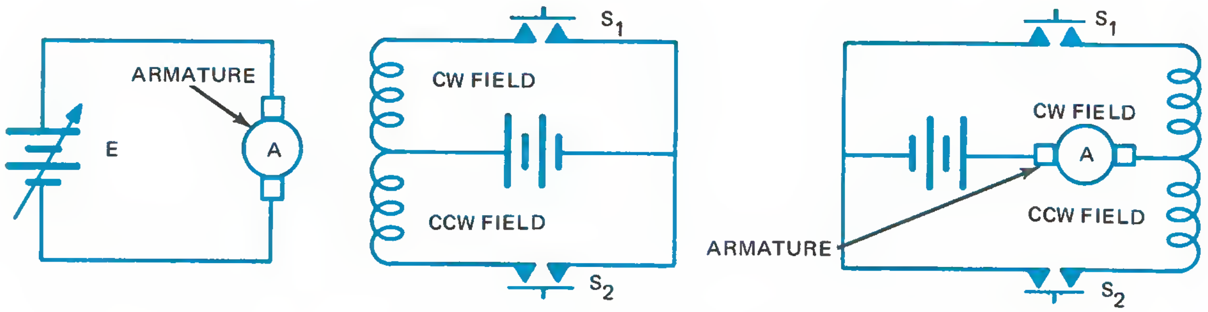


Fig. 8-1 The Split Field DC Motor

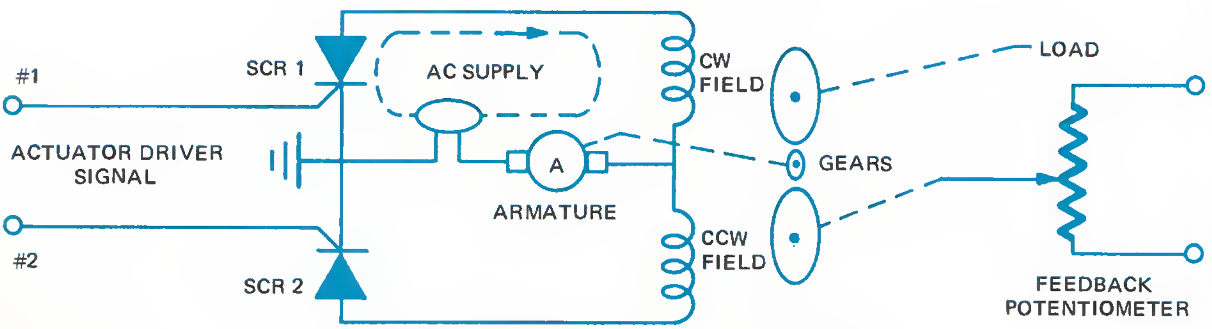


Fig. 8-2 SCR Control of Split Field Motor

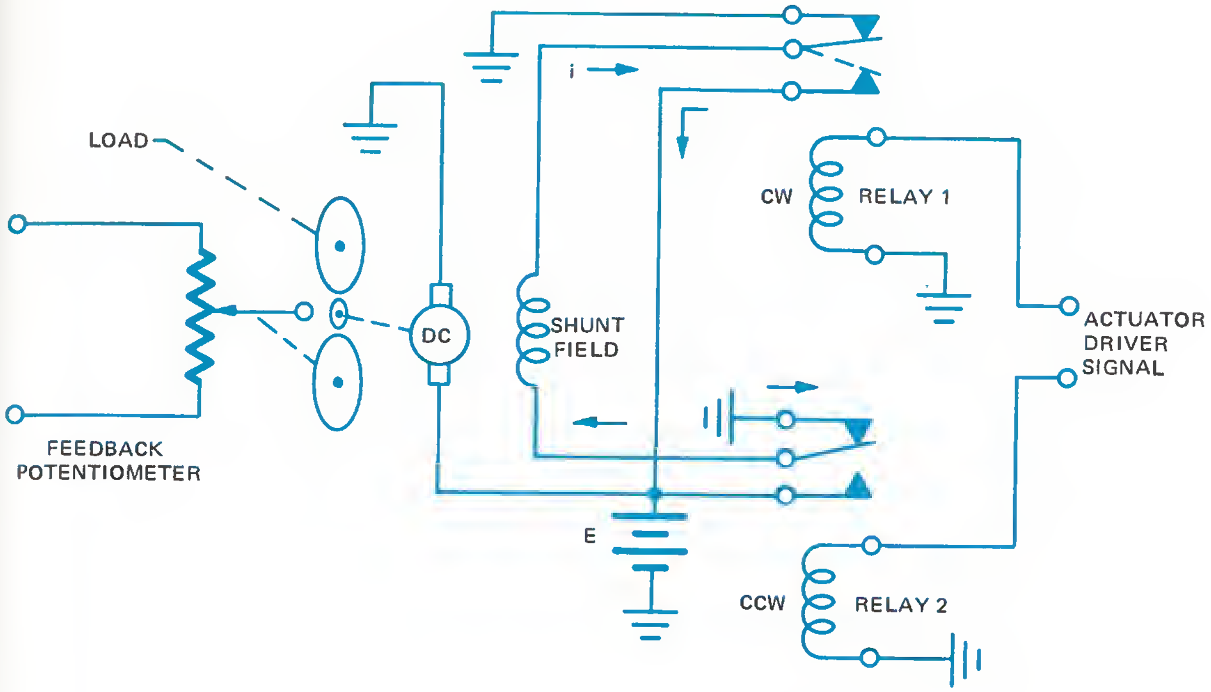


Fig. 8-3 Relay Control of DC Motor

and common, SCR 1 will switch from the "off" state to the "on" state during the half-cycle in which the anode is positive. Even though a positive signal is applied to the gate of the SCR, it will switch to the "off" state during the half-cycle when the AC voltage makes the anode negative with respect to the cathode. With SCR 1 conducting, the current flows through the CW field, causing motor armature rotation in the CW direction. When the error signal is removed from the gate terminal, the armature of the motor stops. The seped of the motor is controlled by the firing angle of the SCR. As the firing angle lessens, the motor speed increases.

If the positive signal is applied between terminal 2 and common, SCR 2 will conduct, causing current to flow through the CCW field. This, of course, would cause the motor to rotate in the reverse direction. The polarity of the error voltage, therefore, determines the direction in which the actuator controls the load. The actuator is mechanically coupled to the load and the feedback potentiometer through a suitable gear mechanism.

Another method of using a DC motor is shown in figure 8-3. The DC motor direction of operation is controlled through relays. The speed of the motor is not controlled, just the direction of operation. When a voltage is applied to the coil of relay 1, the relay energizes, cuasing current to flow through the NC contacts of relay 2, up through the shunt field of the motor, through the NO contact of relay 1 and back to the source. This causes the motor to rotate in the CW direction. Should relay 2 energize, the current would be down through the shunt field of the motor, causing rotation of the motor in the opposite direction.

The shunt motor used in figure 8-3 could be replaced with a permanent magnet motor.

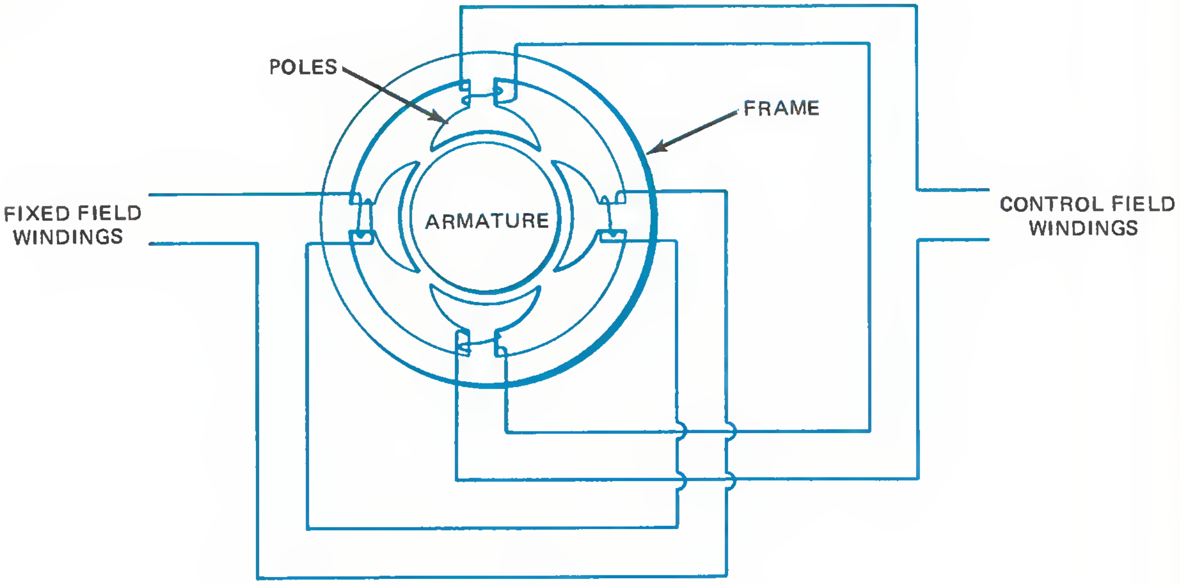


Fig. 8-4 Two-Phase Actuator

The relays would be used to control the direction of current through the armature.

The two-phase AC induction motor, known as a split-phase motor, is the most common type of AC actuator. The motor has two field windings at right angles as shown in figure 8-4. The main field winding, referred to as a fixed field or reference field, is energized by the excitation supply. The control field receives its input from the controller amplifier. Under conditions of zero error, there is no input to the control field and the motor does not rotate. When an error does occur, however, the amplified output of the controller appears across the control field windings. Since both fields are energized, the motor rotates. Speed and direction of rotation are dependent upon the amplitude and the phase of the actuator driver signal.

Proper operation of the motor requires that the two field currents be 90° out of phase with each other. These currents produce a rotating magnetic field which pulls along the rotor of the motor. The direction of rotation of the magnetic field depends on whether the control field current is 90° ahead of or behind the main field current. Displacing the two currents by 90° can be achieved by shifting the phase of the voltage in the amplifier, shifting the phase of the reference voltage in the main field windings, or by a combination of these two methods. These three methods are shown in figure 8-5.

Figure 8-6 shows how a rotating magnetic field is produced by two currents 90° out of phase. Figure 8-6A shows the graph of the control voltage *lagging* 90° behind the fixed voltage. The arrows in the small circles above the graphs indicate the direction of the resulting magnetic field. The magnetic field revolves in a counterclockwise direction. Figure 8-6B shows the graph of the control voltage *leading* the fixed field voltage. Again, because of the phase difference, the field revolves. But this time the rotation of the field is in a clockwise direction. Thus, by changing the phase of the control voltage (either leading or lagging), the direction of the rotation may be controlled.

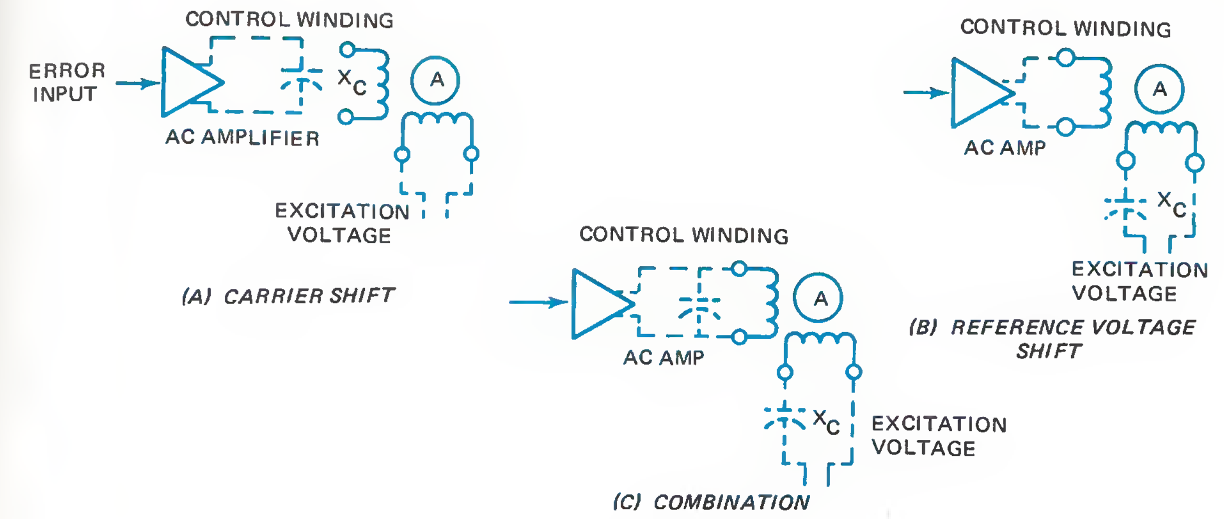


Fig. 8-5 Phase Shift Methods

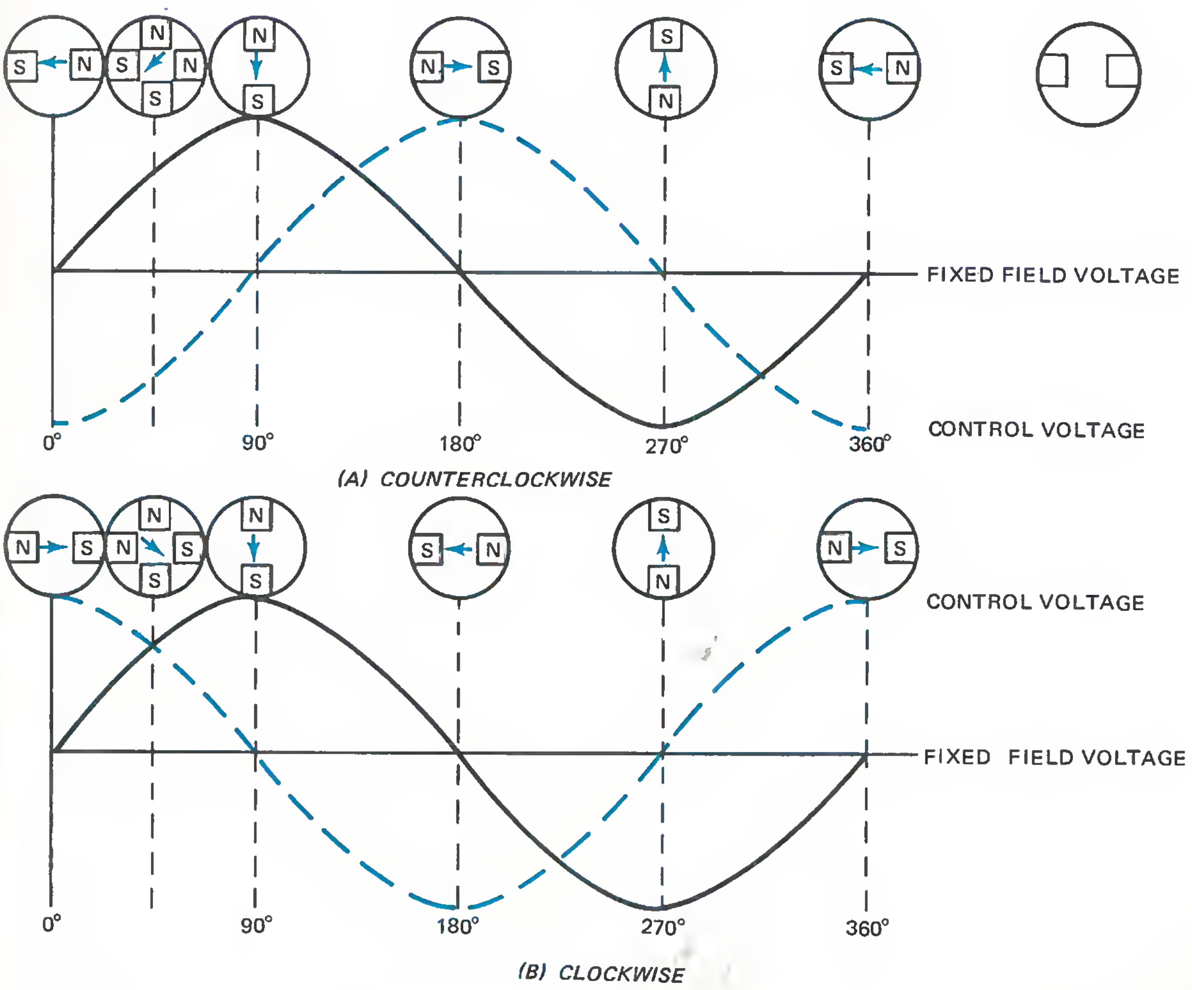


Fig. 8-6 Rotation of Magnetic Field

As the rotating magnetic field cuts across the short-circuited rotor (squirrel-cage type construction) it induces a current in the rotor. The resulting current flow in the rotor generates a magnetic field. The magnetized rotor now attempts to align itself with the composite field created by field windings of the motor. Since the composite field rotates, the rotor is pulled along. The rotor never catches up with the rotating magnetic field. By the time the rotor reaches the position in which it would have been aligned with the composite field, the field has moved on. The rotational speed of the rotor is, therefore, slower than the speed of the composite field—the difference in speed is called the slip of the motor.

The squirrel cage rotor of the two-phase motor is made as small in diameter as practicable to insure low inertia. High-resistance rotor bars are used to help determine the control characteristics and to prevent the tendency to run as a single-phase motor. Their relatively high torque and low inertia make them capable of high accelerations to follow rapidly changing error signals. In most cases the motor speed is much too great for the requirements of the driven load. Consequently, the speed is usually reduced by the use of a gear reduction between the motor shaft and the load. The gear reduction, while reducing the speed, also increases the torque available for driving the load. Gear reductions must be designed for low inertia and minimum backlash to minimize tendencies toward instability.

Two-phase AC actuators generally operate at a high RPM when the control winding is fully energized. Because of the high RPM, and the mass of the motor, the motor may overshoot the desired control value. To prevent overshooting due to inertia or coasting, the motors are damped. Three methods used are viscous dampers, inertial dampers and tachometer dampers.

Viscous damping consists of a low-inertia drag cup rotating in a fixed magnetic field. As the cup cuts the flux of the magnetic field, drag is added.

The inertial damper consists of a drag cup attached to the motor shaft extension. A permanent magnet and flywheel are bearing-mounted separately from the motor shaft. As the motor accelerates or decelerates, the drag cup, by cutting the magnet's flux path, generates eddy currents and creates a magnetic field which causes the permanent magnet to follow the drag cup rotation. The magnet on the same shaft as the flywheel has considerable inertia and tends to lag behind the drag cup, retarding the motor rotation. The inertial-type damper is diagrammed in figure 8-7.

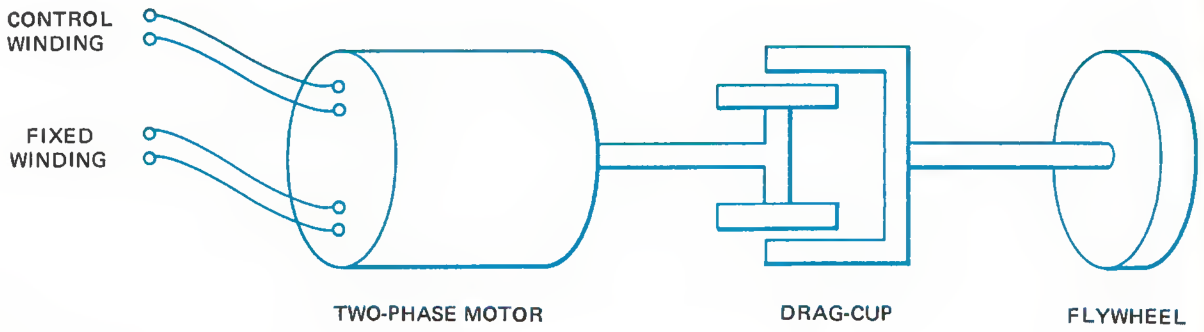


Fig. 8-7 Inertial Damping of a Two-Phase Motor

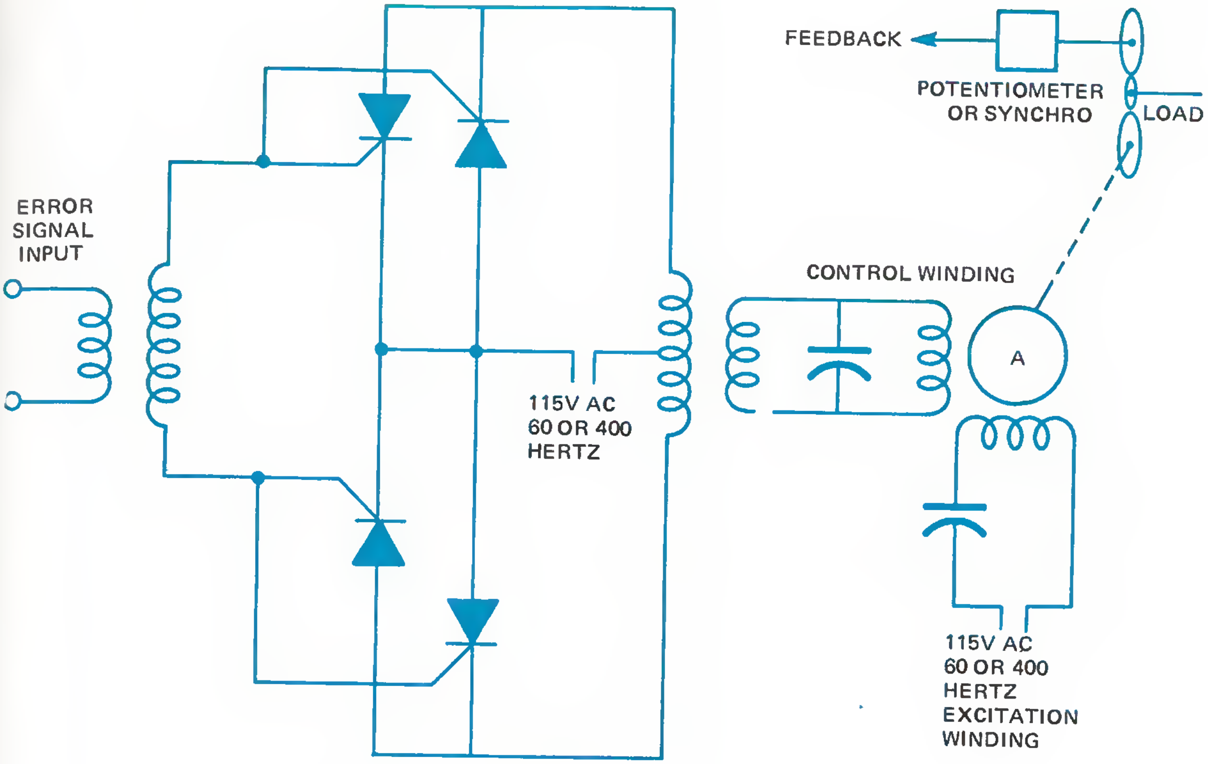


Fig. 8-8 Typical SCR Controlled Two-Phase Motor

Tachometer damping consists of a tachometer generator integrally connected to the shaft of the actuator. Such a unit produces a voltage in the output winding which has the same frequency as the excitation, but which is proportional to the motor speed. The output voltage is fed back to the control actuator to damp the voltage input to the control winding. The higher the RPM of the two-phase motor, the greater the feedback voltage, reducing the net control winding voltage.

A typical SCR controlled two-phase motor is shown in figure 8–8. The error signal is coupled through a transformer to the SCRs. The feedback device may be a potentiometer or a synchro arrangement.

Many types of AC induction and synchronous motors are used in automatic control systems. The induction motor is used because of its extreme ruggedness and high efficiency. The synchronous motor is used in critical speed applications.

MATERIALS

1 Resistor, 2Ω 8W
1 Resistor, 1Ω 8W
1 Capacitor, 5 μF 600W DC
1 Two-phase motor assembly with follow-up potentiometer and 200 to 1 gear ratio or equivalent.
1 Variable transformer
1 Strip chart recorder
1 DC power supply, 0–40V
3 VOMs or FEMs

PROCEDURE

1. Measure the resistance between terminals 1 and 3 of the two-phase motor. Record these data as the resistance of the fixed phase winding, R_f.
2. Measure the resistance between terminals 2 and 4 of the two-phase motor. Record these data as the resistance of the control phase, R_c.
3. Construct the experimental circuit as shown in figure 8-9.

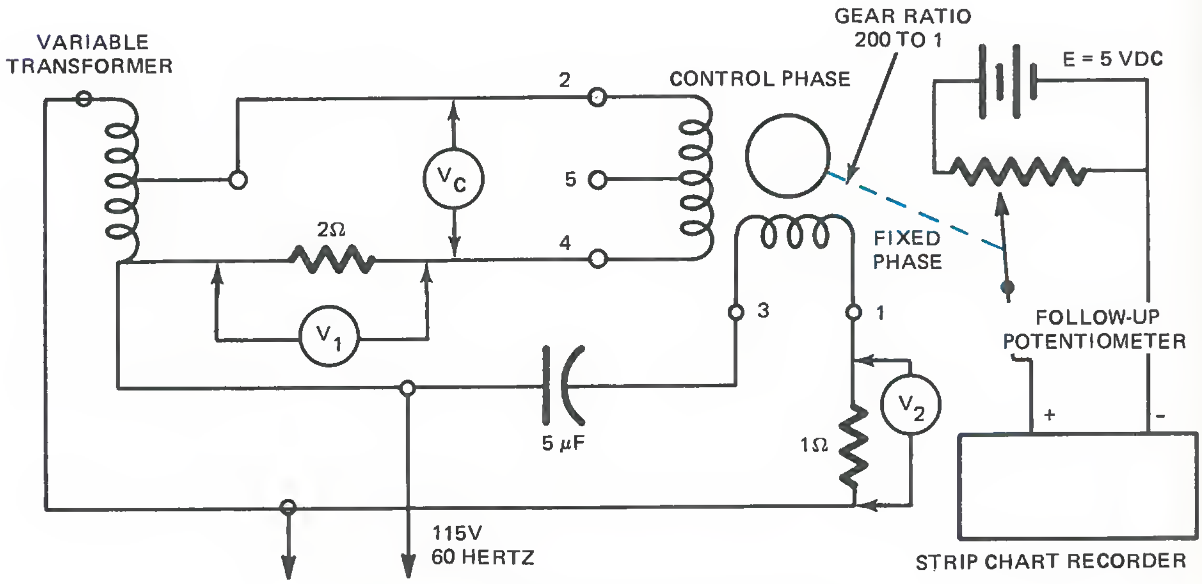


Fig. 8-9 Experimental Test Circuit

4. With the control voltage, V_c, 5 volts, measure and record V_1 and V_2.
5. Calculate $I_c = V_1/2\Omega$ and record these data.
6. Calculate $I_f = V_2/1\Omega$ and record these data.
7. Calculate $P_c = I_c{}^2 R_c$ and record these data.
8. Calculate $P_f = I_f{}^2 R_f$ and record these data.
9. Set the speed of the strip chart recorder to about 10mm/second.
10. Turn the strip chart recorder motor "on" and allow time for one complete revolution of the wiper of the follow-up potentiometer.
11. Turn the strip chart recorder motor "off".
12. From the strip chart recorder trace, determine the time for one revolution of the wiper to occur. t = (no. of mm for one revolution)/10mm/sec.
13. Record these data in the Data Table, figure 8-10, as t.

R_f	R_c	V_c	V_1	V_2	I_c	I_f	P_c	P_f	t	S_1	S_2	Rotation Direction
		5										
		10										
		15										
		20										
		25										
		30										
		35										
		40										

Fig. 8-10 Two-Phase Motor Data

14. Calculate the speed of the follow-up potentiometer wiper by

$$s_1 = \frac{60}{t} \text{ RPM}$$

15. Record these data in the Data Table as S_1.

16. Calculate the speed of the motor by

$$S_2 = (\text{gear reduction ratio})\ S_1$$

17. Record these data in the Data Table as S_2.

18. Determine the direction of rotation of motor shaft and record it in the Data Table as CW for clockwise or CCW for counterclockwise rotation.

19. Repeat steps 4 through 18 for V_c of 10, 15, 20, 25, 30, 35 and 40 volts.

20. Reverse the leads to terminals 2 and 4 of the two-phase motor and repeat steps 4 through 19.

ANALYSIS GUIDE. Plot the control current versus motor RPM. Plot the total input power ($P_c + P_f$) versus motor RPM. Plot the follow-up potentiometer speed versus the motor speed.

PROBLEMS

1. A capacitor in the fixed field of a two-phase, 60 Hertz motor is to be used to provide a 90° phase shift between its fields. If the control field and fixed field inductances are 1 Henry and 2 Henrys, respectively, determine the value of the capacitor required.

2. Draw the schematic of a control circuit used to operate an entrance door to a supermarket using a split-field DC motor. A pressure microswitch under the welcome mat is used to actuate the door. After the door is open 30 seconds, it automatically closes.

3. Determine the gear ratio required to reduce the speed of a two-phase control motor from 2000 RPM to 50 RPM.

experiment 9 FLUID ACTUATORS

INTRODUCTION. Over 90 percent of all machine tools are controlled or operated by fluid power. In this experiment, a fluid actuator will be examined.

DISCUSSION. Fluid power provides flexible and easy control of force, distance and speed. Fluid power can be varied from a few ounces to vast forces above 50,000 tons.

Fluid power has many advantages. It provides an efficient method of multiplying forces. It can provide a constant torque at infinitely variable speeds in either direction with smooth reversals. It is accurate and fast responding. Hydraulic oil provides automatic lubrication while air is clean and safe from fire hazards. Fluid power is economical, efficient and dependable.

An actuator is a mechanism which alters the value of a manipulated variable in response to the output signal of a controller. An actuator, generally, has two functions: First, it translates the output signal of the controller into the value of the manipulated variable. Second, it provides power amplification. An actuator must provide an accurate output position proportional to the input signal. Some of the forces acting on an actuator are inertial forces caused by moving masses, static friction and thrust forces caused by weight and unbalanced fluid pressure.

Fluid actuator power is transmitted and controlled through use of a pressurized liquid or gas. Actuators using liquid pressure and flow are termed hydraulic actuators, while actuators using gaseous pressure and flow are termed pneumatic actuators. Some types of actuators combine electrical and gas or liquid and are termed electropneumatic or electrohydraulic actuators, respectively.

Fluid actuators may be spring-operated or they may be cylinder, valve, or motor-operated. A spring and diaphragm actuator is shown in figure 9-1. The actuator operates from the air pressure output signal of the con-

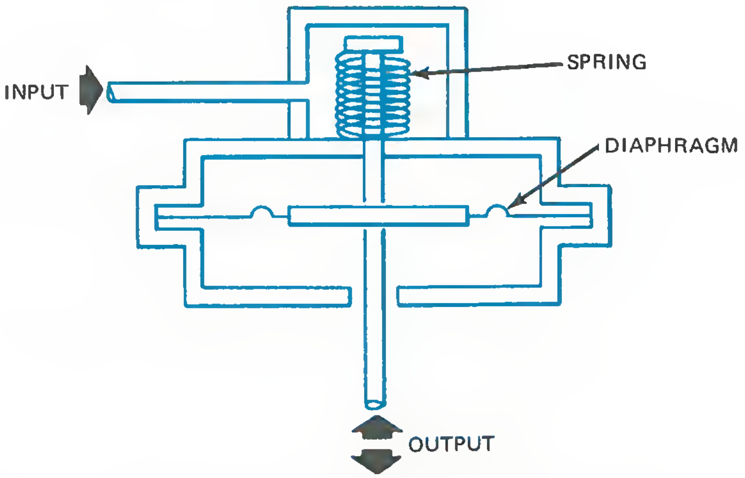


Fig. 9-1 Spring and Diaphragm Actuator

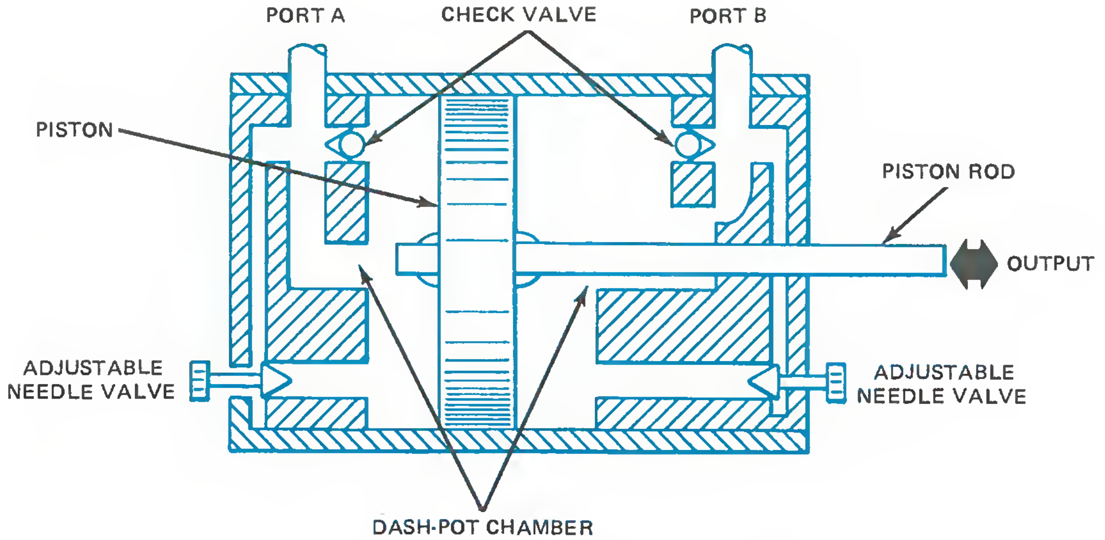


Fig. 9-2 Double Acting Cylinder with Cushioning

troller. The input air pressure acts against the diaphragm and causes a downward force which compresses the spring. At static balance, the force of the air pressure acting against the diaphragm equals the spring compression force. The output displacement or stroke is a linear function of the air pressure, diaphragm characteristics and spring constant. The output movement of the actuator is usually between 1/8 and 4 inches.

A cylinder-type actuator is shown in figure 9-2. This actuator converts fluid power into linear mechanical force and motion. It consists of a piston and piston rod operating within a cylindrical bore. When the output from the controller causes fluid to enter port A, the piston is driven toward the right, and fluid from the opposite side is exhausted back through the controller into the reservoir. When the output of the controller is applied to port B, the movement is to the left. The velocity of a cylinder as it extends or retracts is

$$\boxed{\nu \text{ ft/min} = \frac{\text{fluid flow in gal/min}}{\text{area of piston in sq. in.}}} \qquad (9.1)$$

The force delivered by the cylinder is

$$\text{Force} = \text{pressure} \times \text{area} \qquad (9.2)$$

To prevent excessive shock due to stopping loads at the end of the piston stroke, a cushion is employed at each end of the cylinder. As the cylinder piston approaches the end of the stroke, exhaust fluid is forced through an adjustable needle valve which is set to control the escaping fluid at a given rate. This allows the deceleration characteristics to be adjusted for different loads. When the cylinder is actuated, fluid enters the cylinder port and flows through the small check valve so that the entire piston area can be utilized to produce force and motion.

Cylinders may be single acting, double acting or telescoping type. Hydraulic cylinders are manufactured to produce forces from a few ounces to many thousands of tons.

Figure 9-3 shows an electrohydraulic actuator. The unit operates by applying the electrical output signal from the controller to

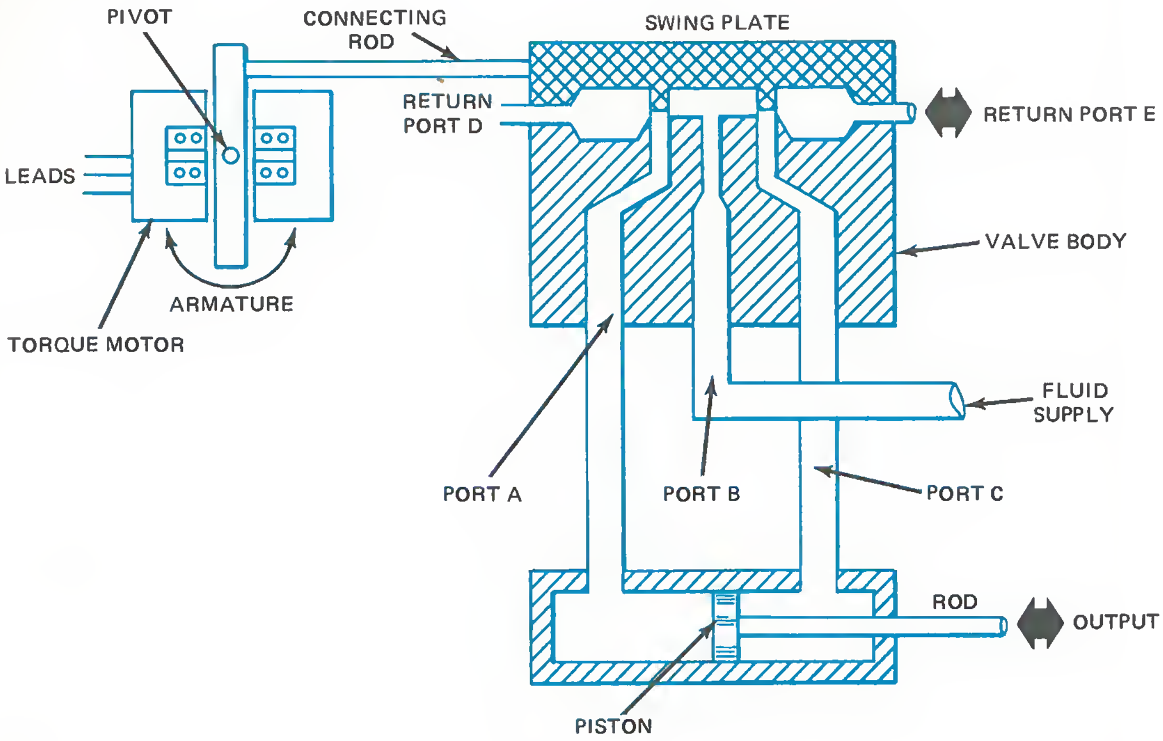


Fig. 9-3 Servo Valve

the coils of the torque motor. As the armature moves about the pivot point, it shifts the swing plate to the right or to the left over the ports. Should the torque motor shift the swing plate to the right, fluid flows from the supply through input port B and through port C. The fluid exerts a pressure on the piston that causes the piston to move to the left. As the piston moves to the left, fluid flows through port A and through port D and is returned to the sump. The maximum movement of the swing plate from the null position is approximately 0.0175 inches. The movement of the swing plate is proportional to the current through the coils of the torque motor. Generally, this type of actuator is utilized when proportional control is desired. There are many variations of electrohydraulic valves and some contain a linear differential transformer, or other type of transducer, to provide a feedback signal that reflects the position of the swing plate or spool. The feedback loop helps to provide a good dynamic response characteristic for servo-controlled systems.

A fluid motor is a device that converts fluid power into mechanical force and motion, usually rotary. Fluid motors operate on the same principles as a fluid pump. The two general classes of fluid motors are the fixed displacement and variable displacement types. For fixed displacement, gear, vane and piston type motors are available. For variable displacement, the piston type is available. The fixed displacement motor displaces a given amount of fluid for each revolution. The speed of the fixed displacement motor depends on its displacement per revolution and the amount of fluid supplied to it. A variable displacement motor is designed with a device that can adjust the displacement per revolution.

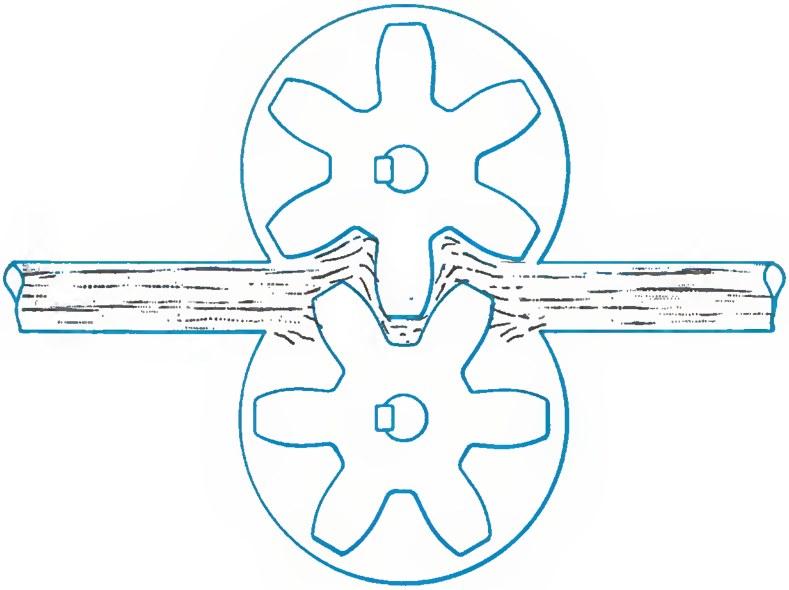


Fig. 9-4 Gear Motor

Fluid motors often have a higher torque-to-inertial ratio than do electric motors. The application of a fluid motor in a system containing a pumping unit is called a hydrostatic transmission system. As with an electrical system, there are two classes: the open loop system and the closed loop system. The open loop system uses the conventional reservoir and directional control valves for directional control. The closed loop system uses a variable reversible type pump to control the speed and direction. Only a small reservoir is needed, because the fluid is retained and circulates within the system.

Fluid motors may be of the gear, vane, or piston type. The gear type is shown in figure 9-4. The gear type motor may operate up to approximately 5,000 RPM. The external gear design consists of a set of matched gears fitted into a machined housing. The gears rotate together as the fluid enters the space between the major and minor diameters. A pressure plate or wear plate on either side of the rotating gears is used to prevent leakage as pressure increases. The internal gear design (Gerotor type) consists of a pair of rotating gears, one inside the other. The Gerotor has a high starting torque characteristic and operates at relatively high speeds.

Piston type motors may be of the axial or radial type. The axial motor uses a valve plate method of displacing fluid, and the radial design uses the pintle arrangement of porting. Piston type motors provide high starting torque and can operate at a much higher pressure than other types. The radial-type piston motor is shown in figure 9-5. Piston-type motors usually have an odd number of pistons — five, seven, nine, eleven or more depending upon the size of the unit. An odd number of pistons is used for a positive starting torque. If the fluid motor is a variable displacement unit, the thrust ring is adjustable. If the unit is a fixed displacement type, the thrust ring is stationary.

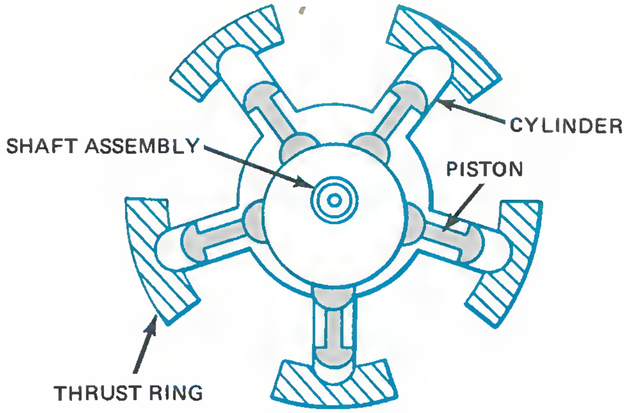


Fig. 9-5 Radial-Type Piston Motor

An axial piston motor is shown in figure 9-6. In the fixed unit the cam plate is stationary, whereas in the variable unit, the cam angle is adjustable. In both the axial and the radial types, a fluid pressure in the motor forces the piston outward, causing the shaft to rotate. The rate at which fluid is delivered to the motor determines its speed.

A vane motor is shown in figure 9-7. Fluid enters the motor at two points 180° apart, and the two exhaust parts are also located 180° apart. Fluid forced into the vane motor pushes against the vanes and causes the rotor and shaft assembly to rotate. Flow directed to the opposite parts will reverse the shaft direction.

A variable-delivery pump may be used with a positive-displacement motor to produce an output position or speed that is proportional to the input. The variable-delivery pump is shown in figure 9-8A. The pump consists of a disk driven by a constant speed electric motor. A number of pistons are attached to the disk and reciprocate in a cylinder body. When the disk and cylinder are

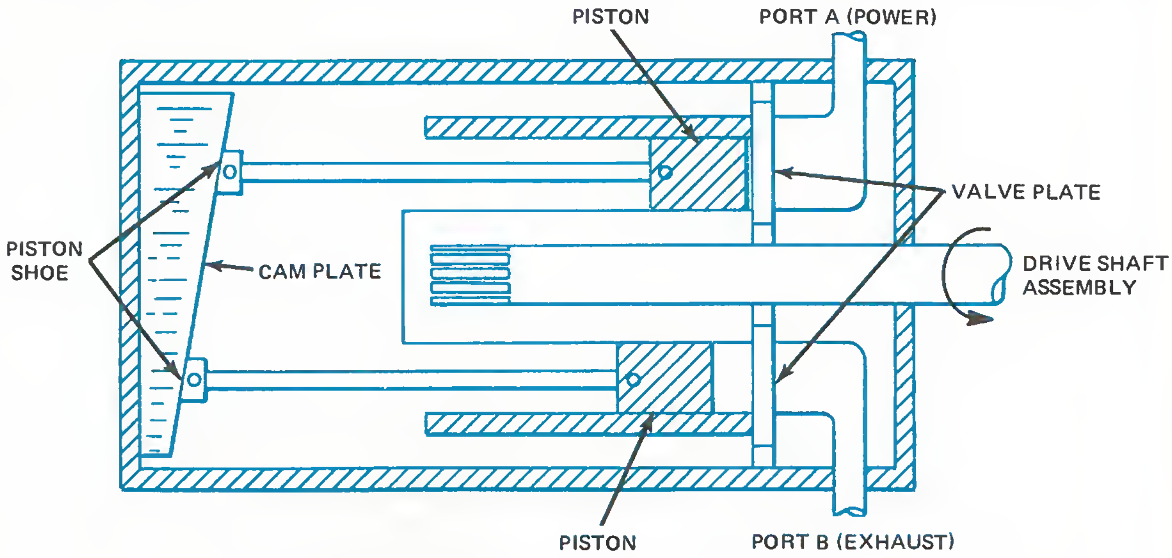


Fig. 9-6 Axial-Type Piston Motor

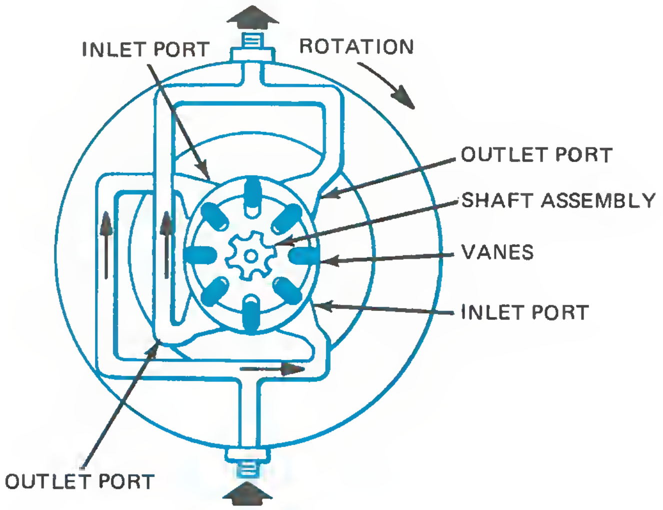
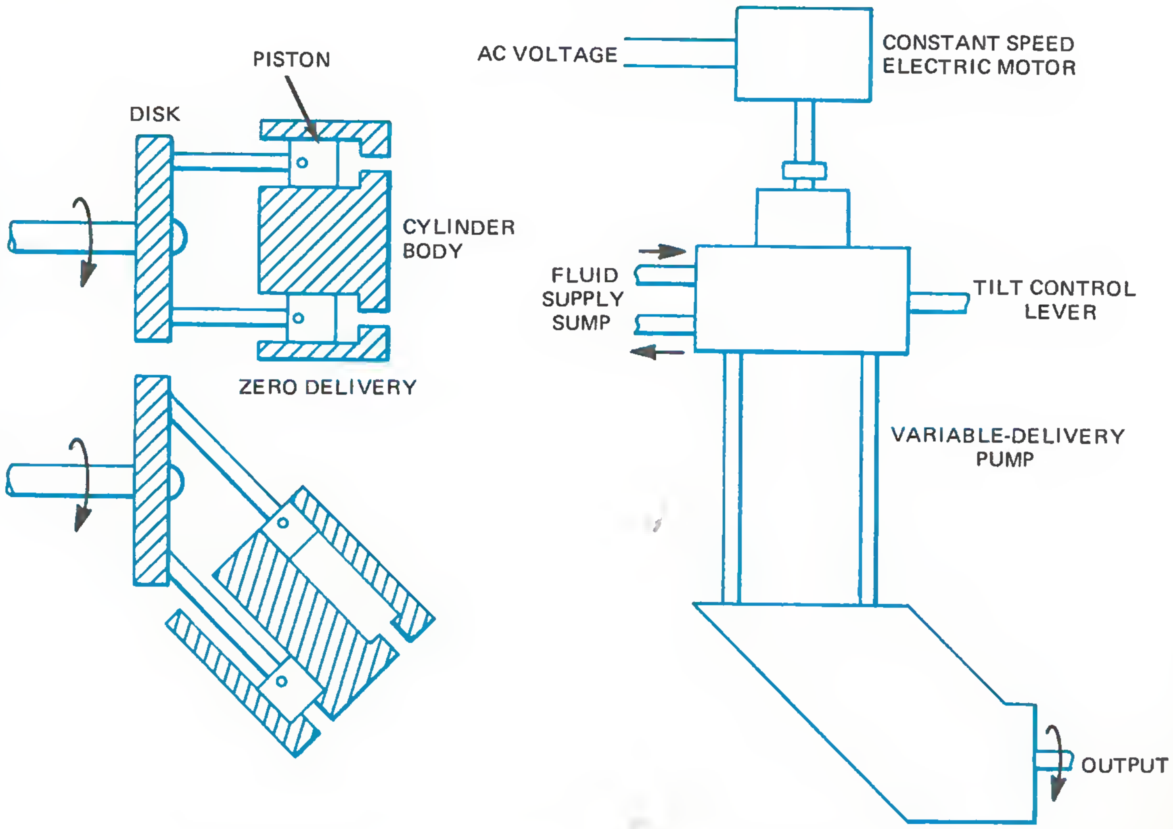


Fig. 9-7 Vane-Type Motor

axial, the pistons remain stationary and there is no fluid flow. When the cylinder body is tilted, the pistons reciprocate and fluid is delivered that is proportional to the amount of tilt. A system using this type of pump is shown in figure 9-8B.



(A) MAXIMUM DELIVERY *(B) POSITIVE-DISPLACEMENT MOTOR*

Fig. 9-8 Variable-Delivery Pump System

MATERIALS

1 Hydraulic supply, 0-500 psi at 4 gal/min
1 Regulator, 0-500 psi
1 Pressure gage, 0-500 psi
1 Flow meter, 0-3 gal/min
1 Hydraulic motor
1 Dynamometer, torque 0-2 in.-lb, speed 500-2000 RPM

PROCEDURE

1. Construct the experimental circuit as shown in figure 9-9.

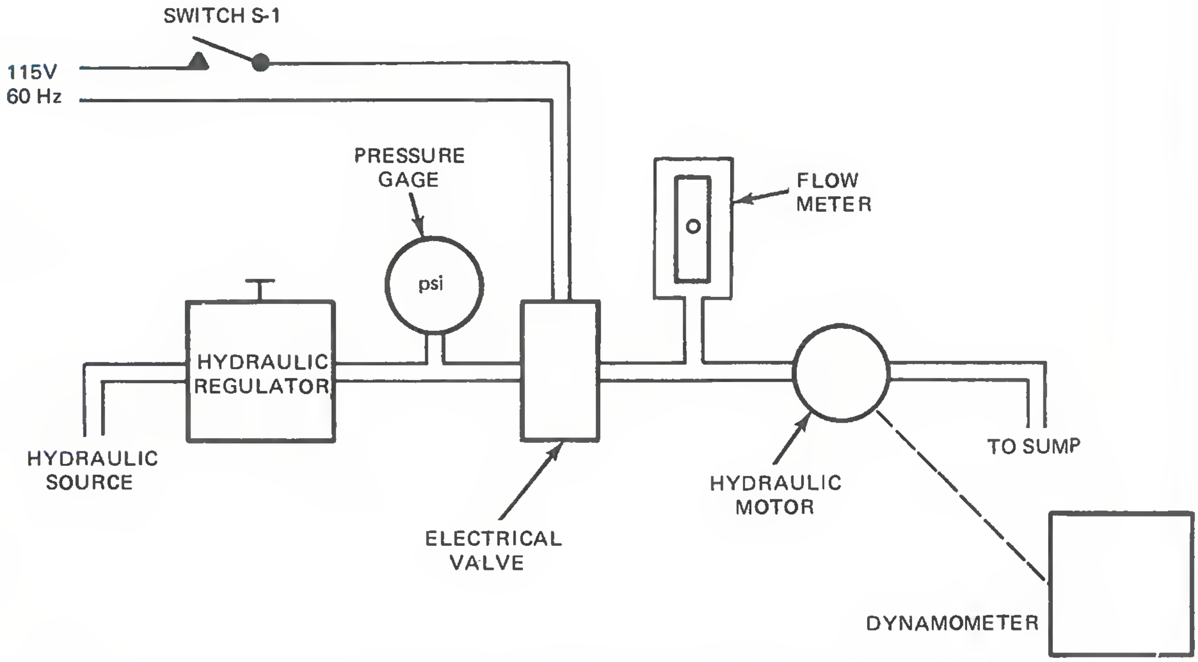


Fig. 9-9 The Experimental Setup

2. Set the dynamometer to provide 1/5 of the motor's rated torque.
3. With S-1 closed, adjust the hydraulic regulator until the speed of the motor is 500 RPM.
4. Measure and record the pressure, psi, and rate of flow, Q, in the Data Table, figure 9-10.
5. Calculate the power-in using the equation

$$HP = QP_1$$

6. Record this value in the Data Table as P_1 HP.
7. Calculate the power-out using the equation

$$HP = \frac{TS}{5250}$$

8. Record this value in the Data Table as P_o HP.

9. Calculate the efficiency using the equation

$$\text{eff} = \frac{P_o}{P_{in}} \times 100$$

10. Record this value in the Data Table as Eff.
11. Repeat steps 2 through 9 for 1000, 1500, 2000 RPM.
12. Repeat steps 2 through 11 for 2/5 rated motor torque and 3/5 rated motor torque.

1/5 Rated Torque

RPM	Q gal/min	psi	P_1 HP	P_o HP	Eff
500					
1000					
1500					
2000					

2/5 Rated Torque

RPM	Q gal/min	psi	P_1 HP	P_o HP	Eff
500					
1000					
1500					
2000					

3/5 Rated Torque

RPM	Q gal/min	psi	P_1 HP	P_o HP	Eff
500					
1000					
1500					
2000					

Fig. 9-10 The Data Tables

ANALYSIS GUIDE. Plot a graph of the rate of flow versus speed for each torque load. Plot a graph of the rate of flow versus the power output for each torque load.

PROBLEMS

1. Calculate the velocity in ft/min of a piston whose area is 4 square inches, if 5 gallons of fluid per minute is being fed into the cylinder.
2. If the resisting force against a piston of a cylinder is 4 tons, how much pressure will be required by the system using a two-inch diameter cylinder to cause the piston to move?
3. How many in.-lb of torque will a gear-type motor produce at 1000 psi if its displacement is 1.0 cubic inch of fluid per revolution? The torque produced by a fluid motor is the product of the pressure in psi and the displacement per revolution in cubic inches divided by 2π.
4. How much horsepower would be produced by the gear motor in problem 3 if the fluid input to the motor is 5 gallons per minute and the speed is 2000 RPM?

experiment 10 SYNCHROMECHANISMS

INTRODUCTION. A synchromechanism is a rotating component known generally as a rotary inductor. In this experiment, some synchromechanisms and their applications will be investigated.

DISCUSSION. Synchromechanisms, commonly called synchros, are a large group of rotating electromechanical machines that combine the principle of the electric motor with the principle of the transformer. Like the motor, the synchro has a set of stationary windings called stators and rotating windings, rotors. The rotor windings are mounted on a shaft. Like the transformer, one winding functions as a primary and the other as the secondary. The type of synchro and its use determines which winding may be used as the primary. When large mechanical driving forces are required, the output of the synchro arrangement is amplified and used to drive an appropriate electric motor. Some other names for a synchro are selsyn, teletorque, autosyn, and diehlsyn.

Systems utilizing synchros may be classified as either torque or control types. A control system uses the synchros to provide electrical information about angular position to a controller unit. A torque system uses synchros to supply the mechanical power to position a light load. The various types of synchros that you may encounter include:

G or TX – Synchro generator or torque transmitter

M or TR – Synchro motor or torque receiver

DG or TDX – Differential generator or torque differential transmitter

DM or TDR – Differential receiver or torque differential receiver

CX – Control transmitter

CT – Control transformer

Military designations of synchros indicate physical size, type of unit, and excitation frequency. A typical synchro designation is 23TDX6. The first two characters, in this case 23, is the diameter of the synchro in tenths of an inch. The alphabetic characters, in this case TDX, describe the synchro as a torque differential transmitter. The frequency of the excitation voltage of a synchro is represented by a 4 for 400 Hertz and, as in this case, a 6 for 60 Hertz. The synchros are frequently represented by symbols or schematic diagrams as shown in figure 10-1.

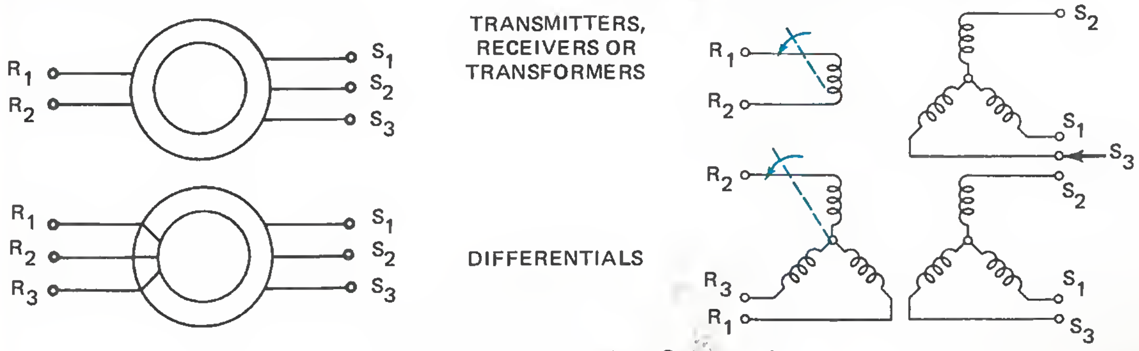


Fig. 10-1 Synchro Schematic

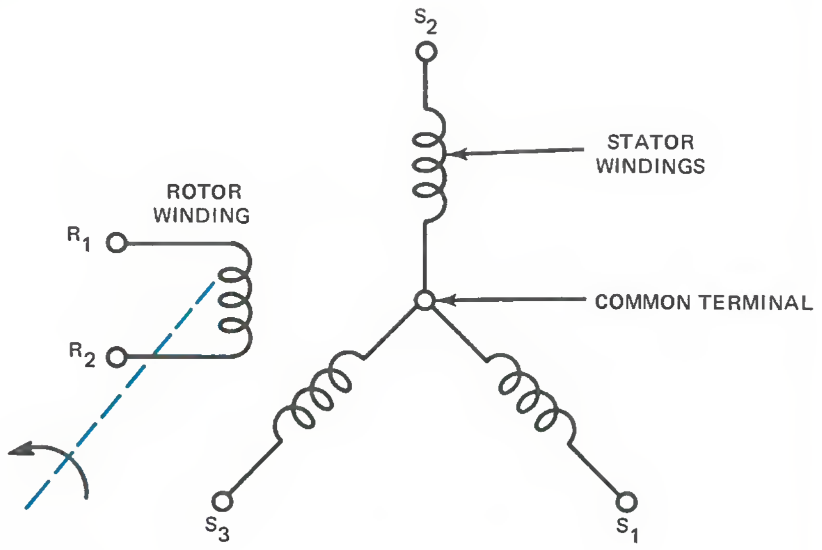


Fig. 10-2 The Synchro Transmitter or Generator

The synchro generator or transmitter shown in figure 10-2 is used as a position-to-voltage transducer. The transmitter has a rotor winding and a wye-connected stator winding. The stator windings are spaced 120° apart. The rotor functions as the primary of a transformer, with the stator acting as the secondary. The stator leads are identified as S_1, S_2, and S_3. The rotor windings are identified as R_1 and R_2.

In operation, the rotor is connected to a source of excitation. The voltage induced in a stator secondary will depend upon the angle at which the magnetic lines of force cut across its turns, and upon the magnitude of the rotor winding voltage. The rotor winding of a synchro is mechanically connected to the rotor shaft. As the shaft is rotated, the angle at which the magnetic lines of force cut the secondaries is varied. Figure 10-3 illustrates the relationship between the position of the rotor and the voltage induced into S_1. The phase of the stator voltage is measured with respect to the rotor voltage (R_1 to R_2).

For reference purposes, the maximum lines of force cut S_1 when the rotor is aligned with the position of S_1. This condition occurs at rotor positions of 60° and 240°. At any other position of the rotor, the coupling between the primary and this secondary will be decreased; therefore, the voltage induced will be less. At 150°, the coupling is decreased to zero; therefore, the voltage induced into S_1 is zero.

If the rotor shaft is rotated in a counterclockwise direction from 150°, the coupling between the rotor winding and the stator winding, S_1, is increased and the polarity of the voltage induced into S_1 is positive. If the rotor shaft is rotated in a clockwise direction, the coupling between the rotor winding and stator winding, S_1, is increased, but the polarity of the voltage induced into S_1 is negative. Therefore, the magnitude and the polarity of the voltage induced into the windings of the stator depends on the angular positions of the rotor windings.

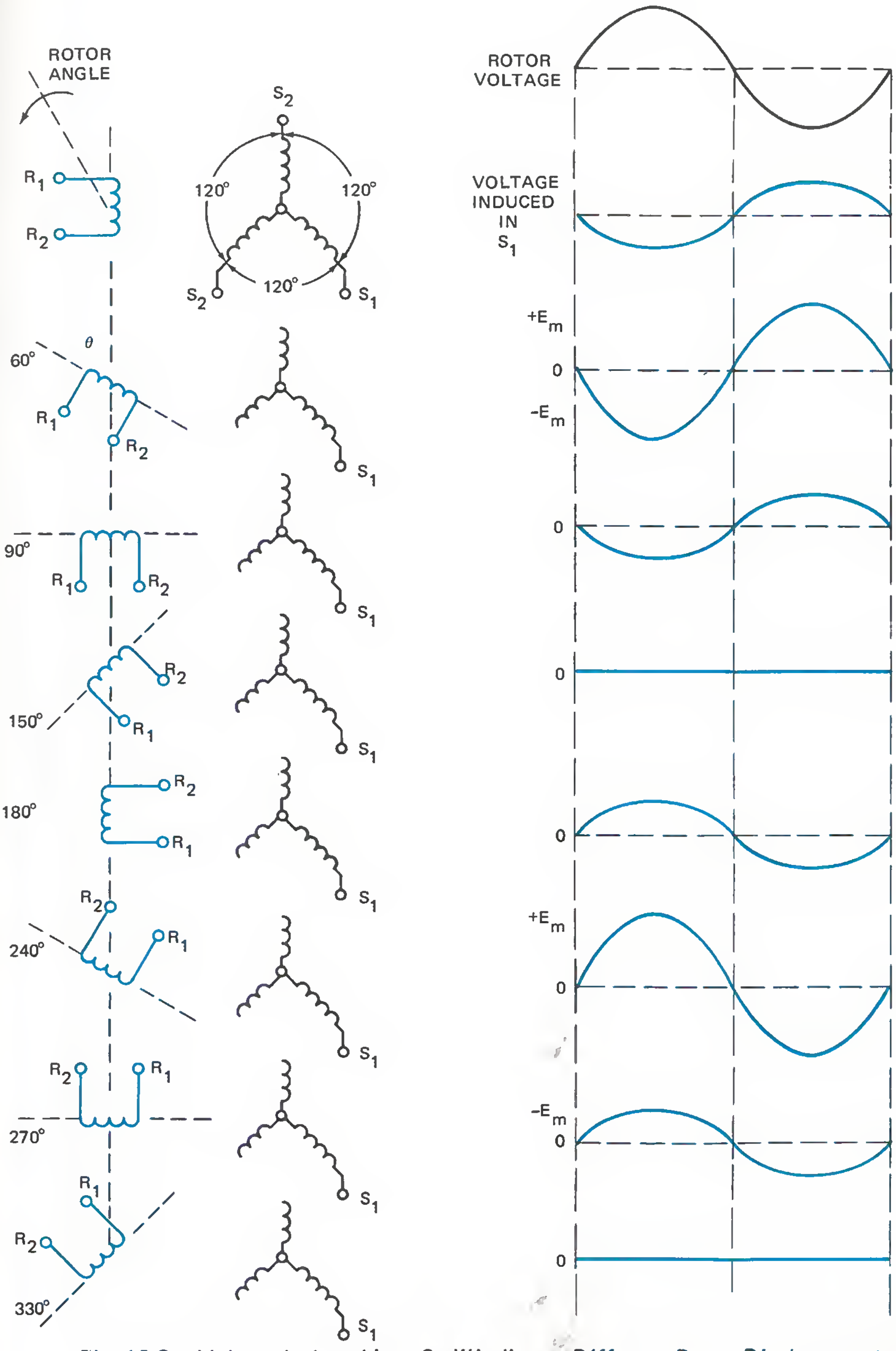


Fig. 10-3 Voltage Induced into S_1 Winding at Different Rotor Displacements

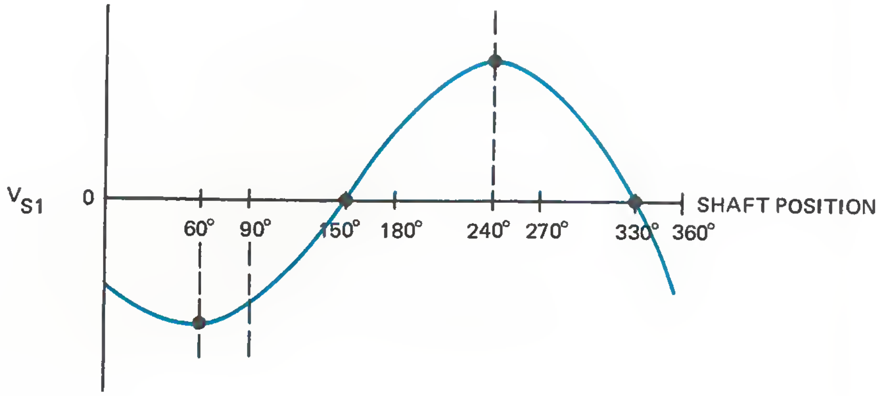


Fig. 10-4 V_{S1} Versus Shaft Position

A graph of the voltage induced into S_1, versus the rotor shaft angle is shown in figure 10-4. From the graph, the voltage induced in S_1 does not adequately identify rotor position. For example, the induced voltage is the same at 180° as 270° and the voltage at 150° is the same as 330°. Therefore, angular position cannot, necessarily, be determined by knowing the voltage of a single winding.

The synchro contains three stator windings spaced 120° apart. As the coupling between the rotor winding and one stator winding is increasing, the coupling to another stator winding is decreasing. The common terminal is not accessible from the outside of the synchro; therefore, it is customary to specify the stator output voltage, i.e., S_1 to S_2, S_2 to S_3 and S_3 to S_1. A representation of the RMS values of the induced stator voltages versus rotor angles are shown in figure 10-5. The portion of the curves above the horizontal axis indicate an induced voltage *in-phase* with the excitation voltage, and the portion below indicates a phase shift of 180° *out of phase* with respect to the excitation. The combination of three terminal-to-terminal voltages will adequately identify the shaft angle, as no two positions of the shaft will have the same voltage relationship. The transmitter's output is voltage and its input is mechanical displacement.

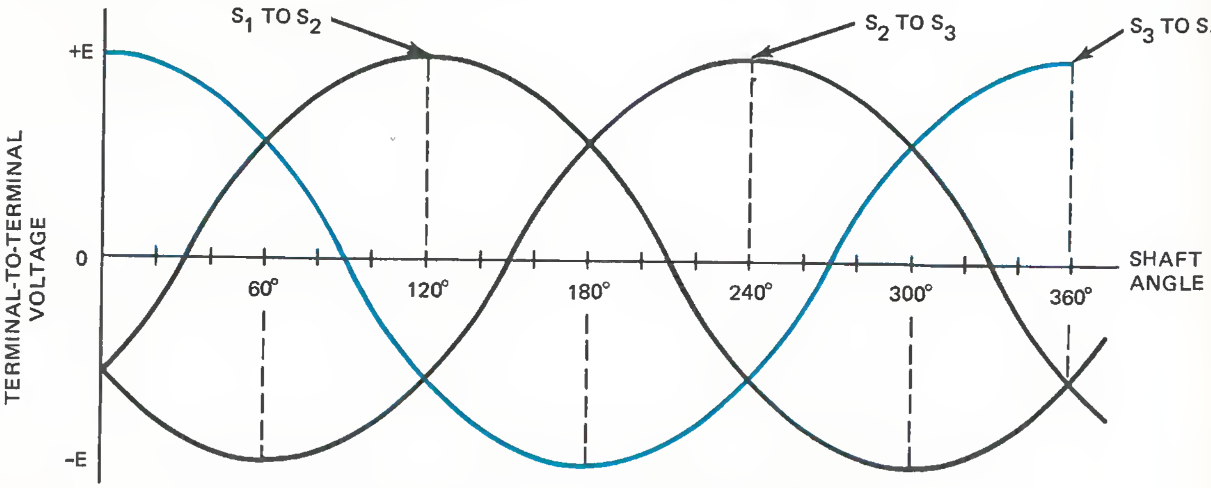


Fig. 10-5 Terminal-to-Terminal Voltage Versus Shaft Angle

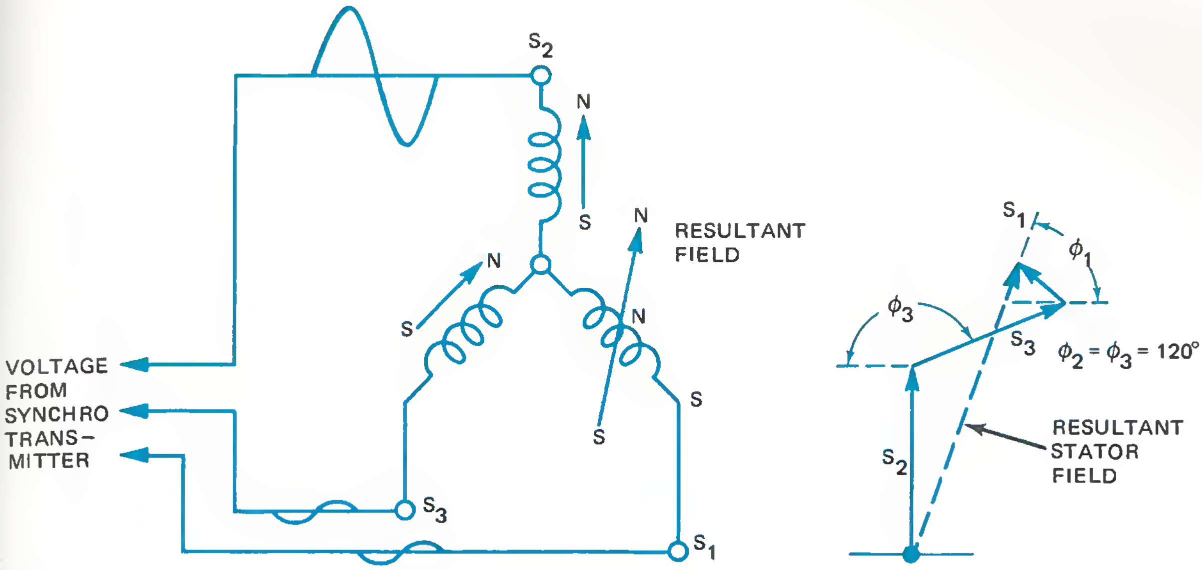


Fig. 10-6 Resultant Magnetic Field due to Stator Voltage

The stator of the synchro transmitter is made of laminated iron that contain slots that do not exactly line up with those of the adjacent laminations. This skewing of the slots is used to prevent the tendency of the rotor to lock in certain positions. The stator coils are divided into three groups which are spaced 120° apart. The rotor windings are connected to a shaft that is usually ball-bearing supported to reduce friction. The rotor is laminated and contains a small air gap between rotor and stator. The excitation is transferred to the rotor through slip rings and brushes.

The synchro receiver or motor is a voltage-to-position transducer. For a given set of stator voltages, the synchro receiver will position its rotor to the corresponding angle. Figure 10-6 shows the magnetic field generated in a synchro receiver stator with an external source applied to the stator windings. The resultant magnetic field strength and direction are determined by the applied terminal-to-terminal voltages. Figure 10-7 shows the magnetic field generated in the rotor windings of a synchro receiver. The field of the rotor is generated by the excitation current. Since

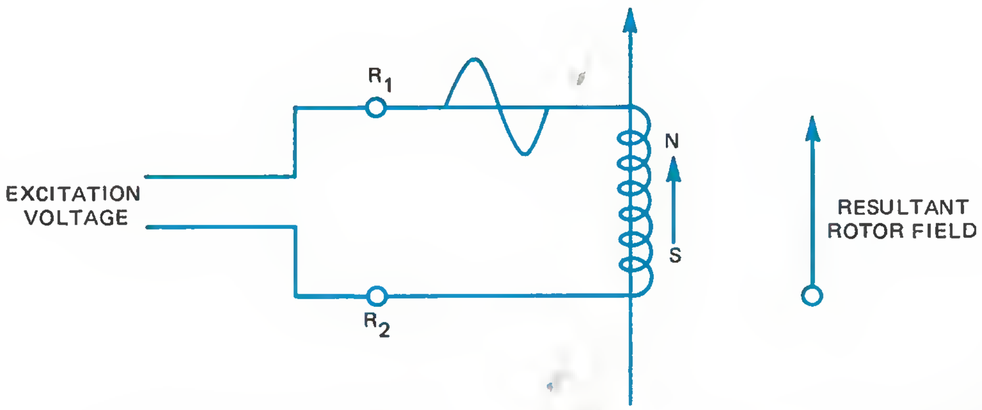


Fig. 10-7 Rotor Magnetic Field due to Excitation Voltage

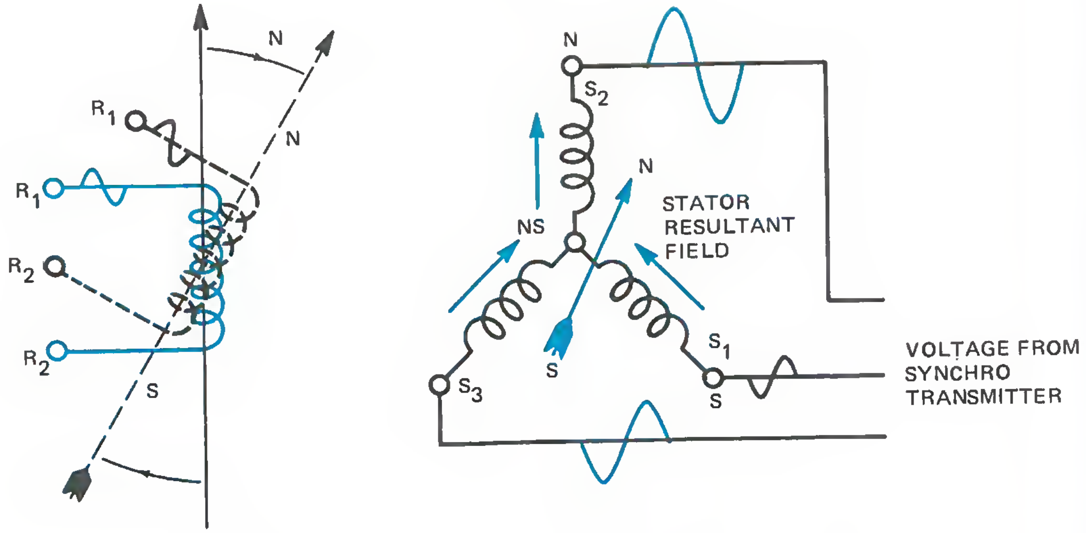


Fig. 10-8 Clockwise Rotation of the Rotor of a Synchro Receiver

the rms value of the excitation voltage applied to the rotor winding is constant, the magnitude of the magnetic field produced in the rotor winding is also constant.

For the magnetic field polarities shown in figures 10-6 and 10-7, the rotor will rotate in a clockwise direction. This action is illustrated in figure 10-8. These polarities of the magnetic field are shown for a half-cycle of excitation voltage. During the other half-cycle, all polarities are reversed and the resultant action is still in the clockwise direction. The forces generated by the magnetic fields produce a motor action with the rotor acting as an armature and the stator as the field. The clockwise rotation continues until the voltage induced into the stator windings by the rotor field exactly cancel the externally applied stator voltages. Since the resultant stator voltage will then be zero, the stator no longer produces a magnetic field and the rotor stops. Therefore, the synchro acts both as a motor and as a transformer. In this manner, the rotor assumes a position determined by the voltage applied to its stator terminals. The synchro receiver is usually used with a synchro transmitter for remote positioning applications. The receiver output is a mechanical torque and its input is a set of voltages.

The physical structure of the synchro receiver is similar to that of the transmitter except that the receiver is provided with an oscillation damper. A flywheel near one end of the rotor shaft damps the oscillation and prevents the motor from running away. Run away in a synchro is an inherent danger that arises from the similarity of the synchro to a single-phase motor. A synchro receiver can be used as a synchro transmitter, but the opposite is not true for 60 Hertz units. Generally, 400 Hertz receivers have little tendency to run away; therefore, they are frequently not provided with dampers.

The synchro transmitter and receiver system may be used for remote positioning of light loads and as remote indicators. Figure 10-9 shows a remote indicator system using synchros. The transmitter rotor winding induces a voltage into the stator windings of the transmitter. These stator voltages are applied to the stator windings of the receiver. The re-

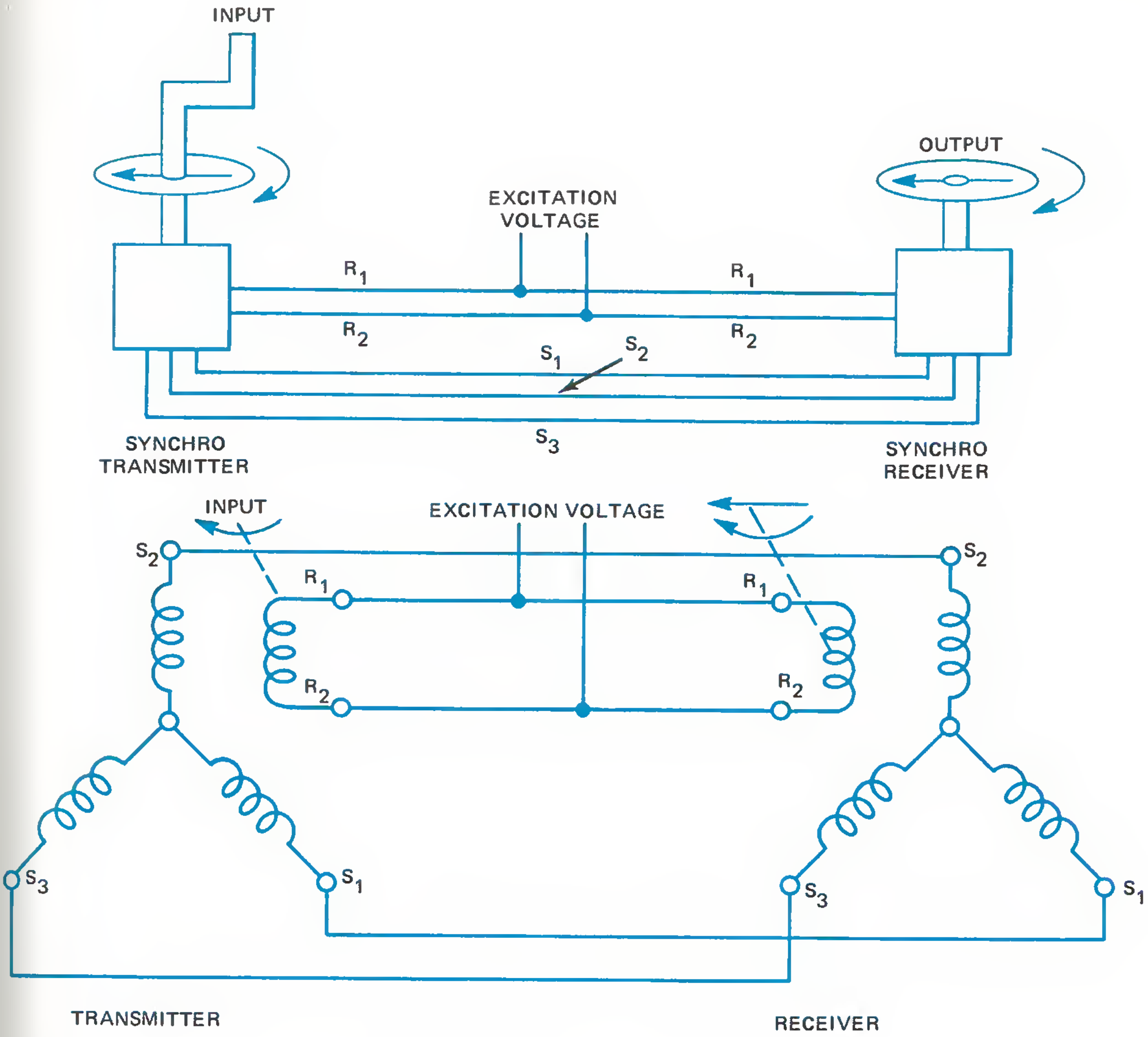


Fig. 10-9 Remote Indicator System

ceiver stator generates a magnetic field that causes the receiver rotor to turn. The receiver rotor turns until it reaches an angular position equivalent to that of the transmitter. At this position, the voltages induced into the receiver stator windings by its rotor are exactly equal and opposite in phase to the voltage applied by the transmitter stator; therefore, the resultant magnetic field is zero and the receiver rotor stops turning. Any motion of the transmitter shaft is duplicated by the receiver shaft.

The synchro receiver is only used for positioning light loads, since heavy loads will exceed the torque capabilities and reduce the accuracy of the system. Where heavy loads are involved, a synchro control transformer is used. Systems using a control transformer are termed *servomechanisms.* The control transformer produces an electrical error signal whose magnitude and phase represent the amount and direction of error between the position of its shaft and the input shaft (transmitter shaft). The error signal is fed to

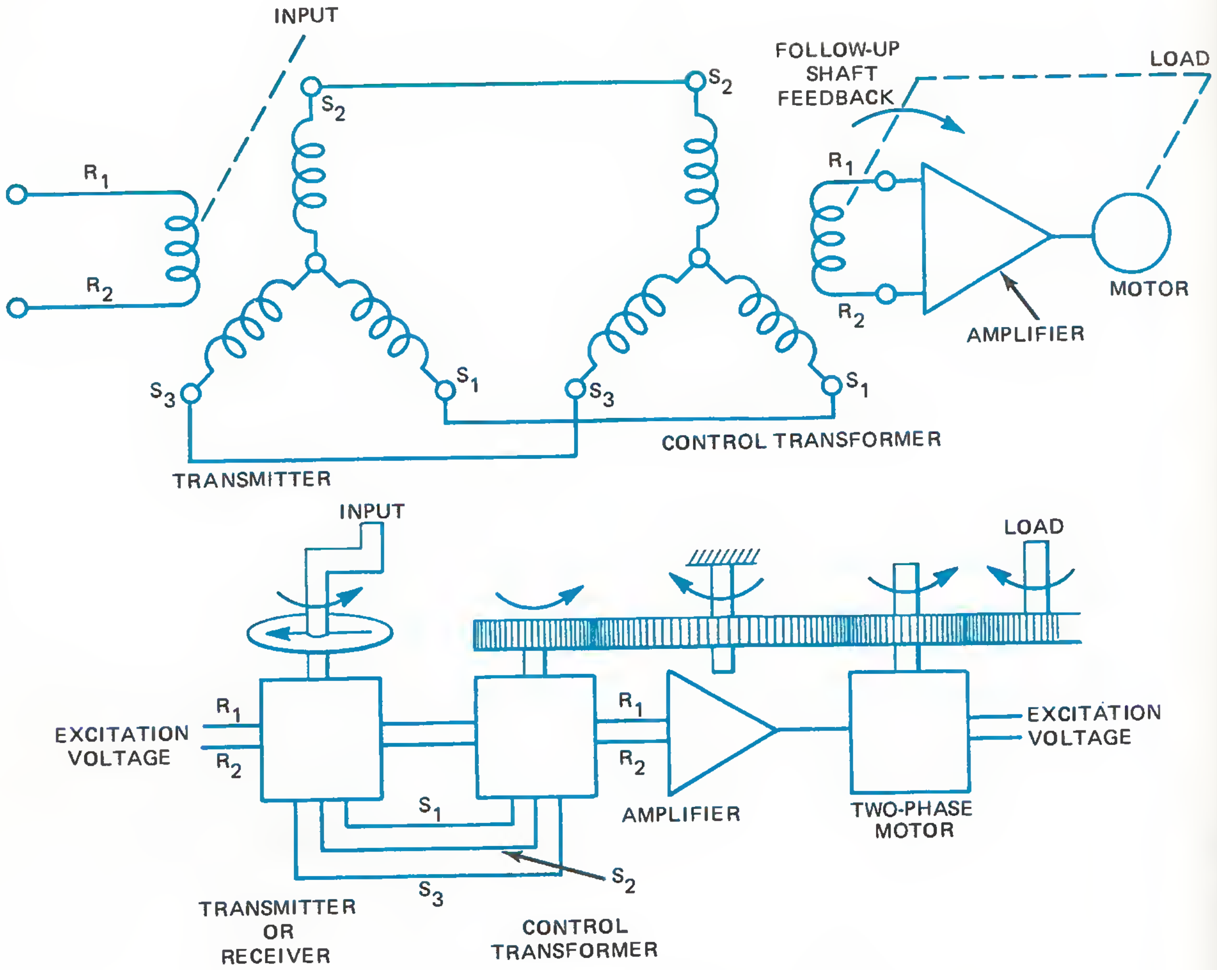


Fig. 10-10 Servomechanism Using Control Transformer

an amplifier that drives a motor which positions the load. The output of the motor is connected to the load and the rotor of the control transformer through a gear box. As the load approaches the desired position, the rotor of the control transformer approaches a position corresponding to that of the input shaft. When the shaft of the rotor of the control transformer is aligned with the rotor of the input shaft, the error signal is zero and the motor stops. A servomechanism is shown in figure 10-10.

The induced voltage in the rotor of the control transformer is determined by its angular position and the direction of the magnetic field produced by the stators. The direction of the stator magnetic field depends on the shaft angle of the transmitter. The results are that the magnitude and phase of the voltage induced into the control transformer rotor (error voltage) depends upon the angular difference of the transmitter shaft and control transformer shaft. The angular difference between the input shaft and the shaft of the control transformer is kept to very small values by the corrective action of the system. For these small values the angular difference, the error voltage generated, is almost linear with respect to displacement. This is shown

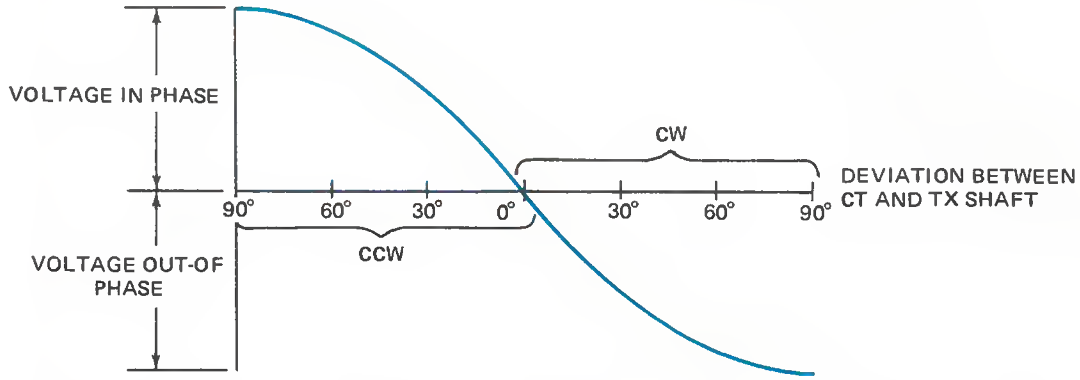


Fig. 10-11 CT Induced Rotor Voltage Versus Angular Difference of CT and TX Shafts

in figure 10-11. There are two positions of the CT rotor at which zero voltage will be induced. When the control transformer is connected into a servomechanism, the correct zero-output, null position must be determined and used. If the correct null position is not used, the system follow-up will cause the amount of error to increase rather than decrease. A method of determining which of the zero-output positions of the CT rotor is correct is as follows:

1. Set the control transformer to one of the zero-output positions. (Electrical zero degrees of the CT is defined as the shaft angle at which the rotor is perpendicular to stator S_2).
2. Rotate the shaft slightly clockwise.
3. If the voltage induced into the CT rotor is 180° out of phase with the excitation voltage applied to the transmitter rotor, the position is the correct null position. If the voltage is in phase, the incorrect null position was selected.

The impedance of the stator and rotor windings of a control transformer are considerably higher than those of the equivalent size transmitter or receiver. A CT should not be used to feed a low-impedance load.

Differential synchros are wound with a three-phase, wye-connected stator and a three-phase, wye-connected rotor. The stator windings function as the primary which derives its magnetizing current from the stator of a synchro transmitter. The rotor windings function as the secondary and has a voltage induced into it whose polarity and magnitude represent the algebraic sum of the angular position of the rotor of the transmitter and that of the differential synchro. The differential synchro can be used as a transmitter for superimposing a correction (algebraic addition) on the signal from a synchro transmitter, or as a differential receiver for indicating the sum (or difference) of the rotation of two separate synchro transmitters. A differential synchro used for subtraction is shown in figure 10-12.

When a differential synchro is used to control a receiver, it is called a synchro differential transmitter. The differential synchro used for addition is shown in figure 10-13.

When a differential synchro is used as the receiver, it is called a synchro differential receiver. A differential synchro controlled by two transmitters is shown in figure 10-14. The differential transmitter and the differential receiver are similar except the receiver has an oscillation damper.

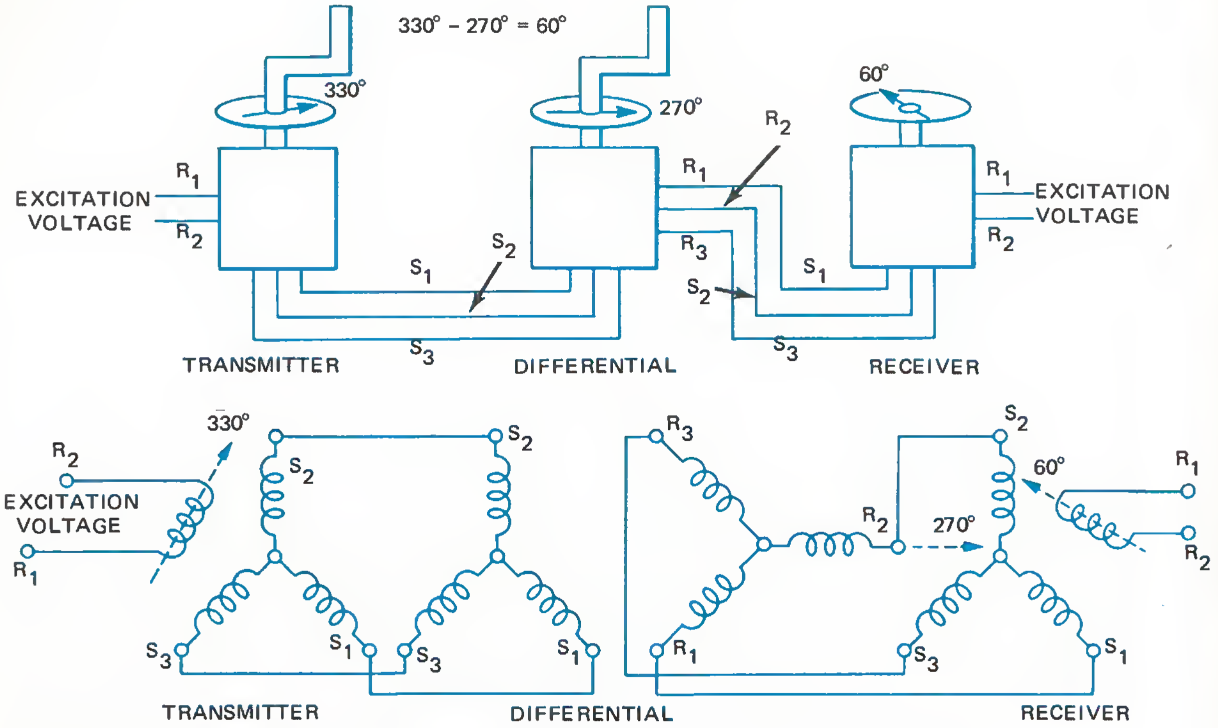


Fig. 10-12 Algebraic Subtractions with Differential Synchro

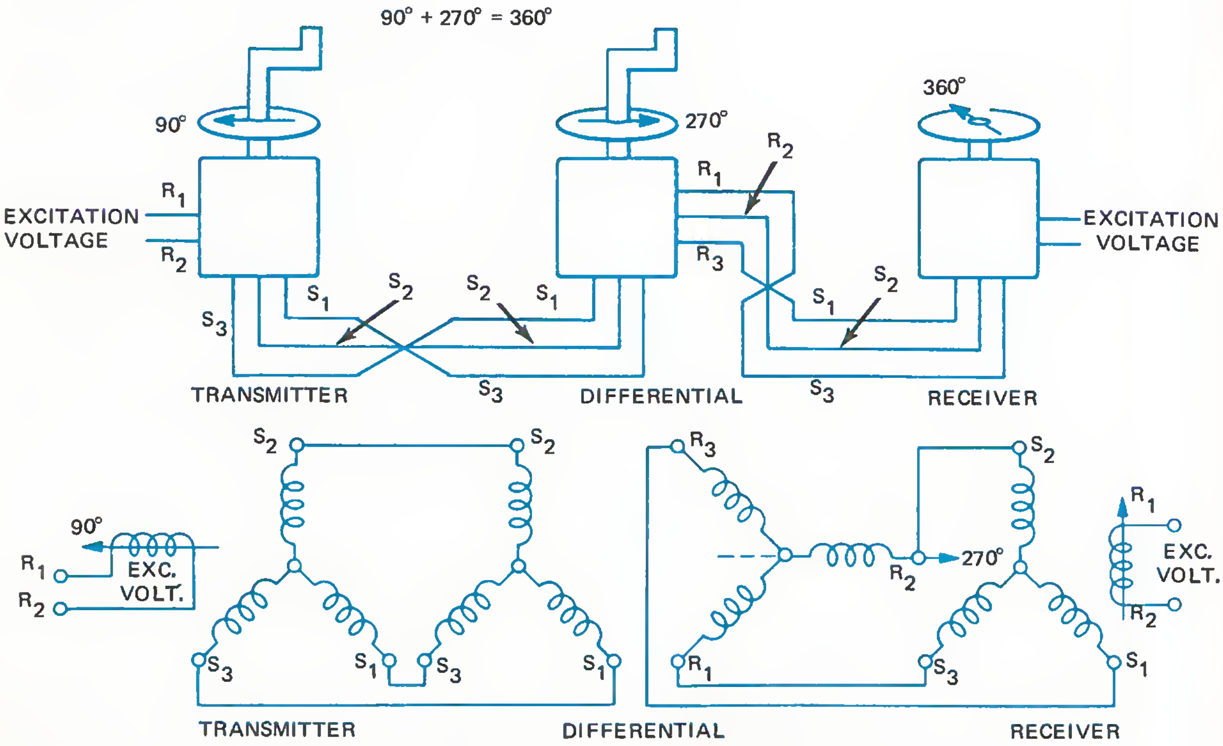


Fig. 10-13 Algebraic Addition with Differential Synchro

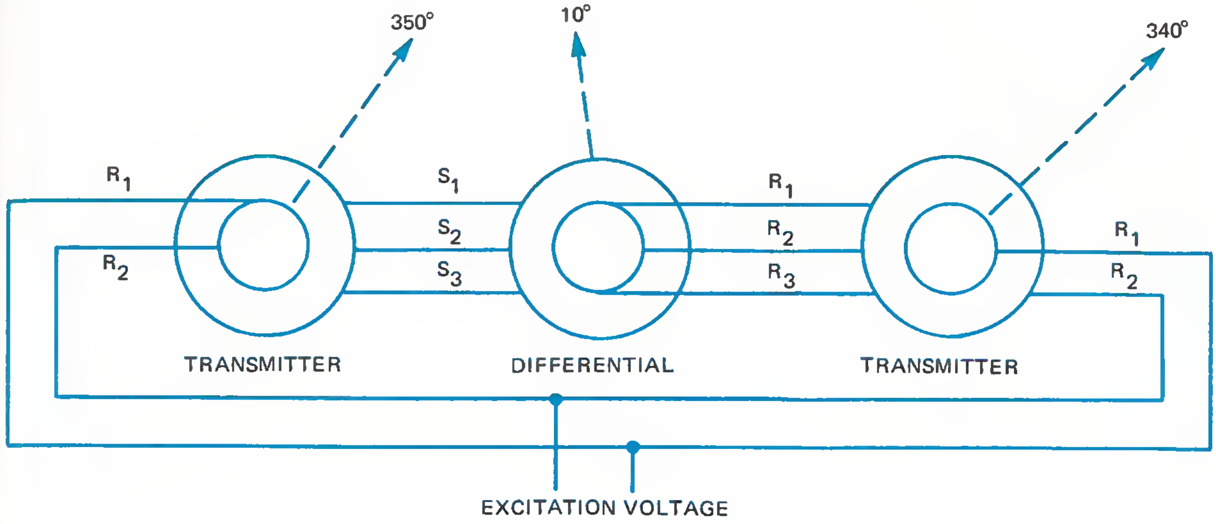


Fig. 10-14 Two-Transmitter Control of Differential Synchro

In analog computers, voltages represent numerical qualities. Therefore, angular position data in the rectangular coordinate system is changed to the polar coordinate system. Conversion from one coordinate system to another is called *resolving* and a device used for this purpose is called a *resolver.* A synchro resolver is shown in figure 10-15. The resolver has two stator windings and two rotor windings. The stator windings, wound perpendicular to each other, function as transformer primaries. The two rotor windings, also wound perpendicular to each other, function as transformer primaries. Like the synchro control transformer, the resolver produces an output voltage rather than rotation. The voltage induced in rotor R_1 is

$$E_{R1} = E_{S1} \cos \theta \pm E_{S2} \sin \theta \qquad (10.1)$$

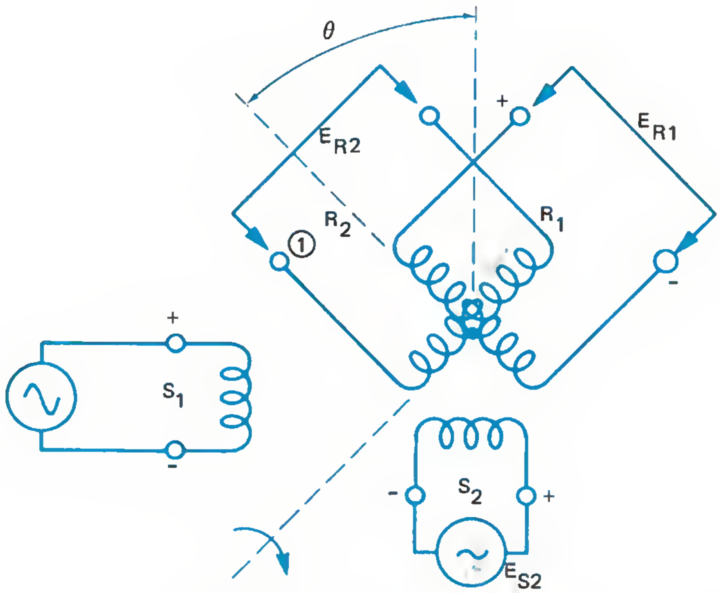


Fig. 10-15 The Synchro Resolver

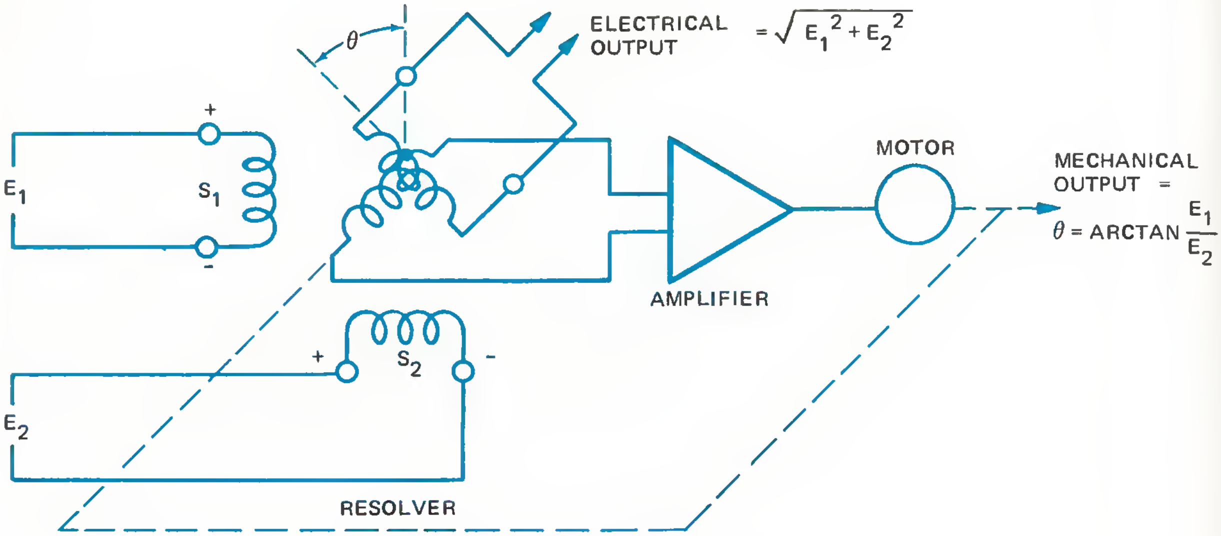


Fig. 10-16 Resolving Rectangular Components into Polar Coordinates

and the voltage induced in rotor R_2 is

$$E_{R2} = E_{S2} \cos\theta \pm E_{S1} \sin\theta \qquad (10.2)$$

The resolver may be used to resolve rectangular coordinates into polar coordinates or as a vector adder. When used as a vector adder, the output may be either electrical or mechanical or both. A resolver system having both outputs is shown in figure 10-16.

MATERIALS

- 1 Synchro, control transmitter 23CX6 or equivalent
- 1 Synchro, control transformer 23CT6 or equivalent
- 2 Pointer assemblies
- 2 Dial assemblies, 0-360°
- 1 Isolation Transformer 115 volt 60-Hertz (1:1 turns ratio)
- 1 Oscilloscope
- 1 VOM
- 1 Breadboard

PROCEDURE

1. Construct the experimental circuit shown in figure 10-17.
2. Connect an AC voltmeter between terminals S_1 and S_3 of the control transmitter.
3. Rotate the synchro rotor until the voltmeter reads approximately zero. The synchro may not be at 0° or 180° on the dial.
4. Remove the voltmeter from the circuit, connect S_3 to R_2 and connect the voltmeter between S_2 and R_1.
5. If the voltmeter reads more than the line voltage, rotate the rotor 180° and repeat steps 2, 3 and 4. If the voltmeter reads less than the line voltage, proceed with next step.

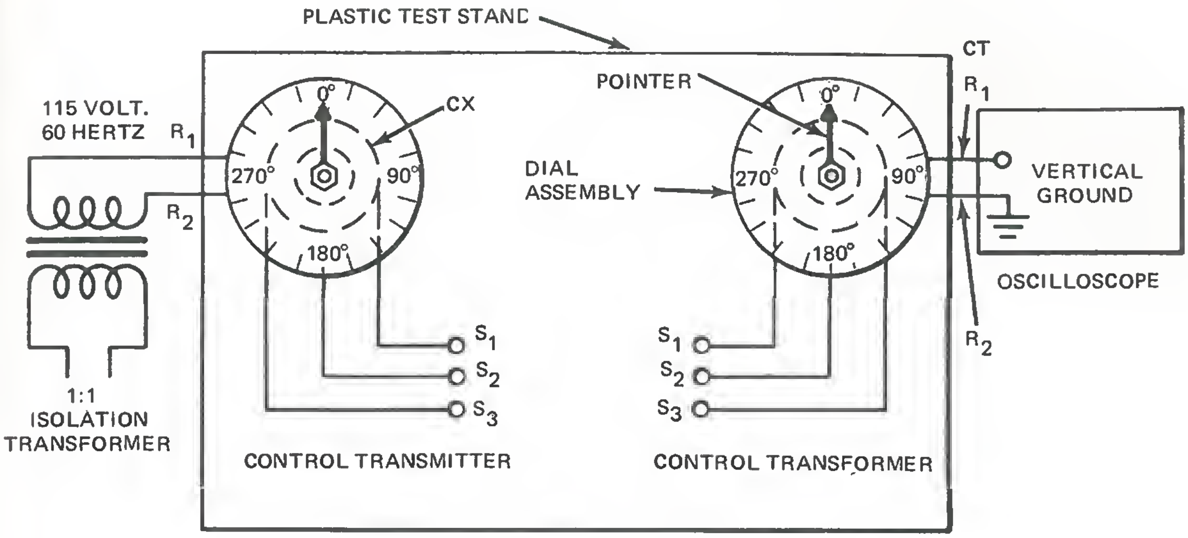


Fig. 10-17 Experimental Circuit

6. Remove the voltmeter from the circuit, disconnect S_3 from R_2 and connect the voltmeter between S_1 and S_2.
7. Very carefully, rotate the synchro rotor until the voltmeter reads a minimum on the lowest scale.
8. Without disturbing the rotor position, adjust the dial to zero degrees and secure it to the rotor shaft. This completes zeroing of the control transmitter.
9. Connect the voltmeter from R_1 to S_1 of the control transformer and connect R_2 to S_2.
10. Connect S_1 and S_2 to the line voltage.
11. Rotate the rotor shaft until the voltmeter reads approximately zero.
12. Remove the voltmeter from the circuit, connect S_1 to S_3 and connect the voltmeter between R_1 and R_2.
13. Connect S_1 and S_2 to the line voltage.
14. Very carefully, rotate the synchro rotor until voltmeter reads a minimum on the lowest scale.
15. Without disturbing the rotor position, adjust the dial to zero degrees and secure it to the rotor shaft. This completes zeroing the control transformer.
16. Connect S_1, S_2 and S_3 of the control transmitter to S_1, S_2 and S_3 of the control transformer.
17. Connect R_1 and R_2 of the control transformer to the input of an oscilloscope.
18. With CT set at zero degrees, set CX to zero degrees and measure the CT output voltage (R_1 to R_2) with the oscilloscope. Record the results in figure 10-18.

Control Transmitter		Control Transformer			
Mechanical Input	Direction of Shaft Rotation	Mechanical Input	Direction of Shaft Rotation	Voltage Output	Phase
0°	–	0°	–		
5°	CW	0°	–		
10°	CW	0°	–		
15°	CW	0°	–		
15°	CW	5°	CW		
15°	CW	10°	CW		
15°	CW	15°	CW		
0°	–	0°	–		
5°	CCW	0°	–		
10°	CCW	0°	–		
15°	CCW	0°	–		
15°	CCW	5°	CCW		
15°	CCW	10°	CCW		
15°	CCW	15°	CCW		
5°	CCW	5°	CW		
5°	CW	5°	CCW		
180°	–	180°	–		
185°	CW	180°	–		
185°	CW	185°	CW		
180°	–	180°	–		
175°	CCW	180°	–		
175°	CCW	175°	CCW		

Fig. 10-18 The Data Table

19. Determine the phase relationship of this output voltage with respect to the line voltage (R_1 to R_2 of the control transmitter rotor). Record the results in figure 10-18 as in-phase or 180° out of phase.

20. Take the data indicated in figure 10-18 with the CT and CX settings indicated in the table.

ANALYSIS GUIDE. Plot a graph, similar to figure 10-11, of the control transformer output voltage versus the degree of deviation between the transmitter shaft angle and the control transformer shaft angle (CT shaft at zero degrees).

PROBLEMS

1. What is the purpose of a synchro transmitter?
2. What is the purpose of a synchro receiver?
3. What is the purpose of a synchro control transformer?
4. What condition determines whether a CT or TR is used in a synchro system?
5. What is the purpose of a differential control transmitter? Receiver?

experiment 11 MONITORING DEVICES

INTRODUCTION. In order for a person driving an automobile down an interstate highway to know his speed, the automobile must possess a speedometer. The speedometer is a monitoring device that indicates the forward speed of the auto. In this experiment some of the monitoring devices used in industry will be examined.

DISCUSSION. The effectiveness of a process or control system can only be achieved when each component of the system is functioning properly. To evaluate effectiveness a method of monitoring the controlled variables must be employed. The two methods used for monitoring are indicators and recorders. An indicator visually displays the value of a controlled variable and is used when no permanent record is required. Recorders are used when a record of the value of the controlled variable over a period of time is required. The indicating and/or recording of the value of the controlled variable at a distance by remote transmission is called telemetry.

The use of an instrument to monitor the value of the controlled variable is called instrumentation. In order for the instrumentation system to monitor the controlled variable satisfactorily, the characteristics of the instrument must be known. These characteristics are generally divided into two types: static and dynamic. The static characteristics pertain to the instrument's ability to measure variables that are not changing. The dynamic characteristics pertain to the instrument's ability to measure variables that are changing.

Important static characteristics of an instrument are: accuracy, sensitivity and reproducibility. Accuracy is the ability of the instrument to indicate or record the true value of the variable being measured. The static error of an instrument is the deviation of the instrument reading from the true value of the variable. Static error may be expressed as

$$\%\ \text{Static error} = \frac{\text{Instrument reading for full scale value of the variable}}{\text{Actual full scale value of the variable}} \times 100 \tag{11.1}$$

Sensitivity is the smallest change in the value of the variable being measured to which the instrument will respond. The range of values of the measured variable within which the measuring instrument does not respond is called the dead zone. The ability of an instrument to indicate or record identical values of the variable when the conditions are repeated is called reproducibility. The gradual change in the indicated or recorded value, during a time in which the true value of the variable does not change, is called drift.

Some important dynamic characteristics of the instrument are its responsiveness and fidelity. Responsiveness is the ability of the instrument to respond to changes in value of the variable being measured. The period of time during which the instrument does not respond is called the dead time. The slowness of the instrument to respond to a change in the variable being measured is called lag. Fidelity is the ability of the instrument to faithfully indicate or record a changing value of the variable. The dynamic error of an indicator or recorder is the deviation between the

instrument's changing output and the changing input. The dynamic error may be expressed as

$$\%\ \text{Dynamic Error} = \frac{\begin{array}{c}\text{Change in instrument's}\\ \text{Reading for a given change in measured value}\end{array}}{\begin{array}{c}\text{Actual change in the}\\ \text{given measured value}\end{array}} \times 100 \qquad (11.2)$$

Because of the size and complexity of industrial process equipment and control systems, the transmission of data indicating the value of the controlled variable from one point to a remote location has become important. Differential forces, flow rates, position information and level are some of the values usually transmitted. Transmission systems may be electrical, electronic, pneumatic, hydraulic, optical or electromagnetic.

Indicators may be constructed with a stationary scale and a moving pointer, or a moving scale and a stationary pointer. Figure 11-1 shows the various arrangements. The accuracy of the indicator is improved by calibrating the scale in smaller increments. Jeweled pivots and precision gears are used in the more expensive units. A mirror placed behind the pointer is used to correct for parallax. The same means used to position a pointer on a scale is used to position a pen of a recorder.

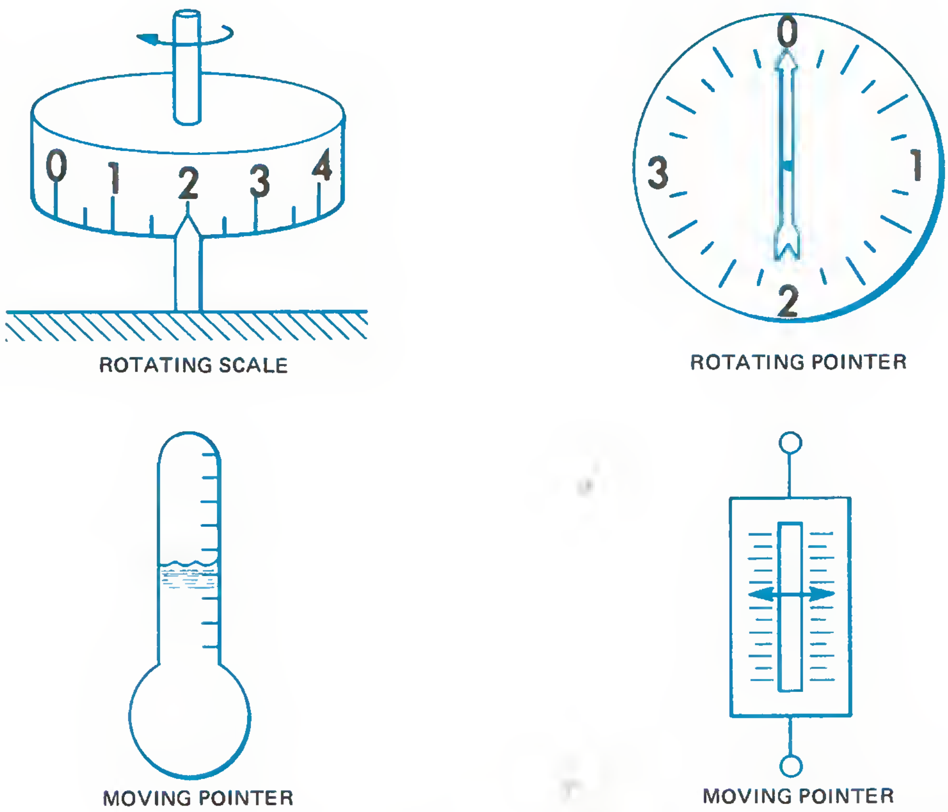


Fig. 11-1 Some Pointer and Scale Arrangements

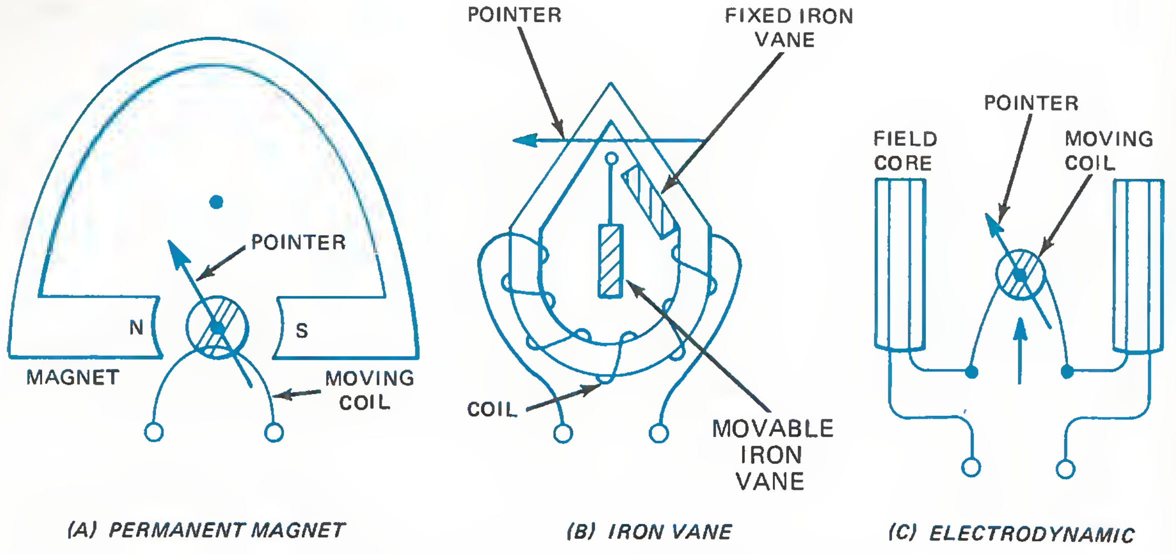


Fig. 11-2 Electrical Indicator Movements

In electrical indicators, there are three types of movements used for indicating current or voltage: the permanent-magnet coil movement, often called the D'Arsonval movement; the iron vane movement, and the electrodynamic, often called the dynamometer, movement. The permanent-magnet movement is shown in figure 11-2A. This movement is designed for measuring DC and rectified AC. The permanent-magnet movement is rugged, sensitive and less expensive than other types of movements.

The iron vane movement is shown in figure 11-2B. The movement is designed for measuring AC currents and voltages directly. The movement is rugged, sensitive and used for general purposes.

The electrodynamic movement is shown in figure 11-2C. This movement is the same as the permanent magnet type except the magnet is replaced with an electromagnet coil. The movement is designed for measuring AC or DC voltages or currents without the use of rectifiers. One of the advantages of this movement is its accuracy.

Remote indicating systems using synchros generally employ a synchro torque transmitter and a synchro torque receiver. The shaft of the receiver is mechanically connected to a pointer that rotates about a calibrated dial.

Fluid pressure or vacuum indicators use either the Bourdon tube, bellows or a diaphram type movement. The Bourdon tube movement is shown in figure 11-3A. The tube may be a flattened semicircle type, a flat spiral type or a helical spiral type. The flattened semicircle type is used for low pressure application, the flat spiral type is used for medium pressure, and the helical type is used for higher ranges.

The bellows movement is shown in figure 11-3B. The bellows are made of light gage materials and may have large effective areas. Because of this, they can develop the large forces needed to strain them through the desired distance. This gage is usually used for relatively low pressures.

A diaphragm movement is shown in figure 11-3C. The diaphragm type movement is

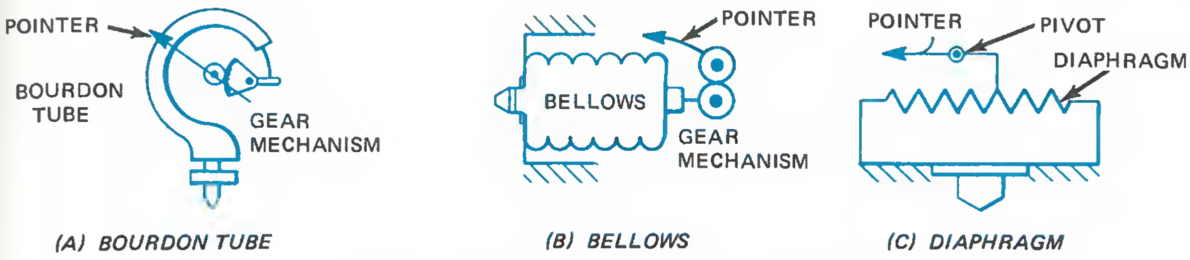


Fig. 11-3 Pressure Indicator Movements

used where the movement of the diaphragm is generally small. It is used in many differential pressure measurements. This gage is usually used with low pressures.

Many other indicating instruments are used in industry, i.e. monometers, thermometers, lamps. The type of controlled variable to be measured, the accuracy required, the sensitivity, the responsiveness, and the fidelity of the measurement will determine some of of the characteristics the indicator must possess to do the job. When the variations in the controlled variable to be monitored are too rapid to read, or are extended over a long period of time, a recorder is used to provide a permanent record of the change. The permanent record may be analyzed at a future time and corrections made in the control or process system for further operation.

The choice of a recorder to monitor a given process or system depends on the desired accuracy, speed of response, the time during which the operation is to be monitored, and the type of signal to be monitored.

All recorders consist basically of: (1) A measuring unit which includes a means of receiving the input signal which reflects the value of the controlled variable. It may use the signal directly or amplify the signal to drive a recording device actuator. (2) An actuator which drives the recording device. (3) A recording device which records the desired signal. (4) A recording medium which is the means of storing the recorded signal. (5) A chart drive which has a mechanism for advancing or rotating the recording medium as a function of time. A block diagram illustrating a recorder is shown in figure 11-4.

The most common means of measuring the input signal to a recorder are the moving coil or galvonometer movement, the null-balance movement, and the force balance movement. The type of measuring unit to be employed depends on the type and characteristics of the signal.

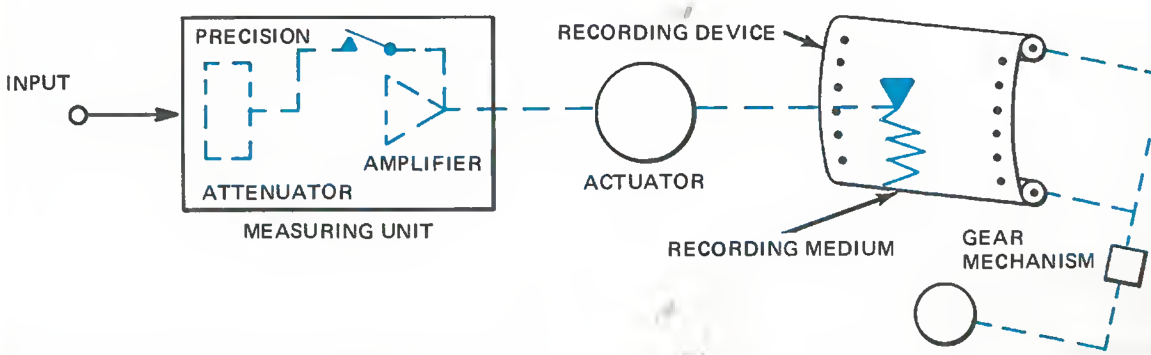


Fig. 11-4 Block Diagram of Recorder

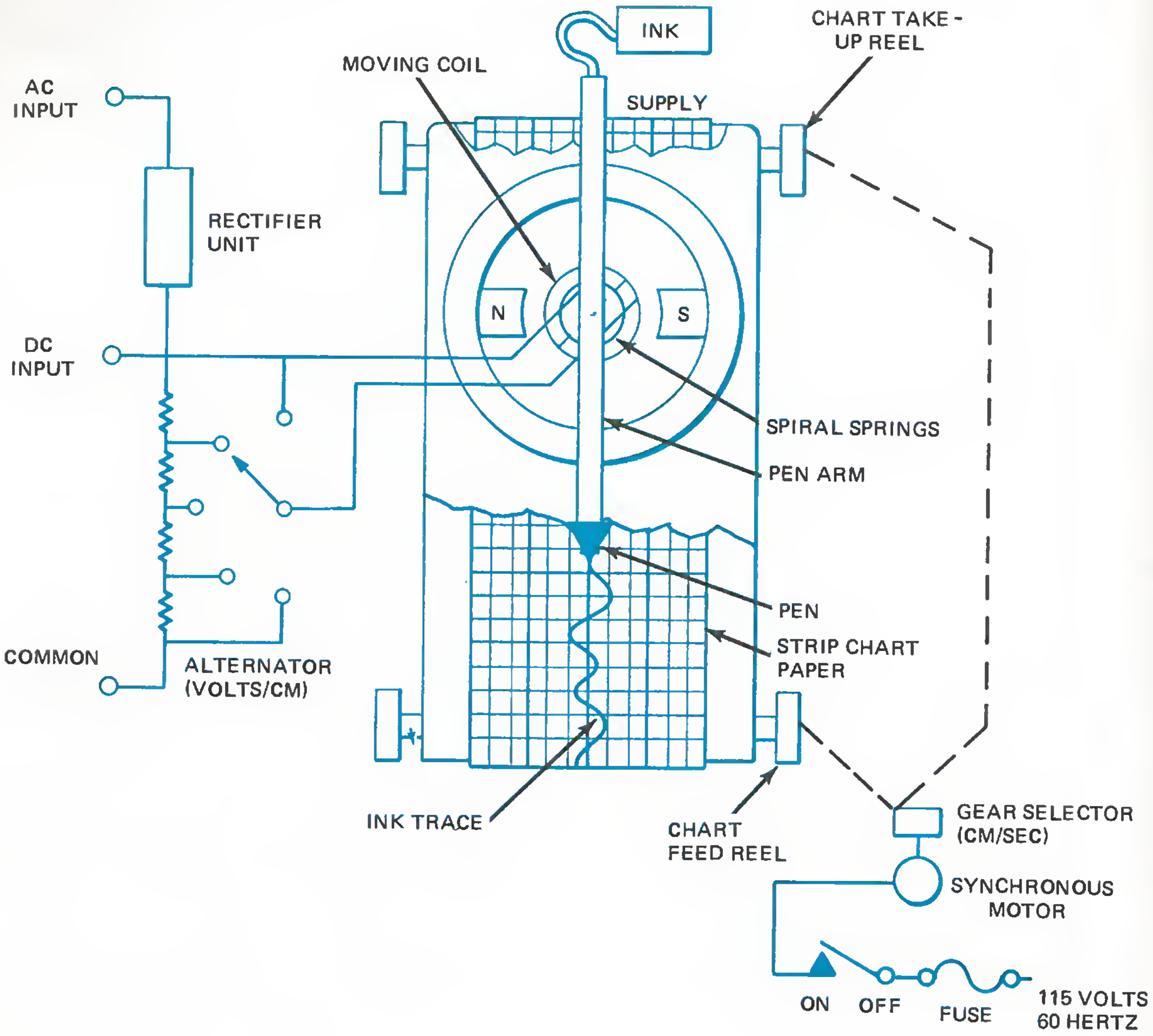


Fig. 11-5 Moving Coil Recorder

A moving coil type recorder is shown in figure 11-5. The recorder is capable of measuring DC and AC voltages. As current flows through the coil, it rotates, deflecting the pen arm while the pen spiral springs oppose the rotation of the coil. The greater the amplitude of the incoming signal, the greater the resulting degree of rotation of the pen arm. When the spiral spring forces are equal to the rotational force produced by the signal current flowing through the moving coil, the pen comes to a rest. The chart paper is moved by a synchronous motor that is coupled to the take-up and feed reels through a gear mechanism. The gear mechanism allows the speed of the chart paper (mc/sec) to be varied. Therefore, the resultant pen trace is a function of the incoming signal amplitude and chart speed (time). The attenuator allows the operator to set the sensitivity (volts/cm) of the recorder.

A force-balance type recorder is shown in figure 11-6. With no input signal, the posi-

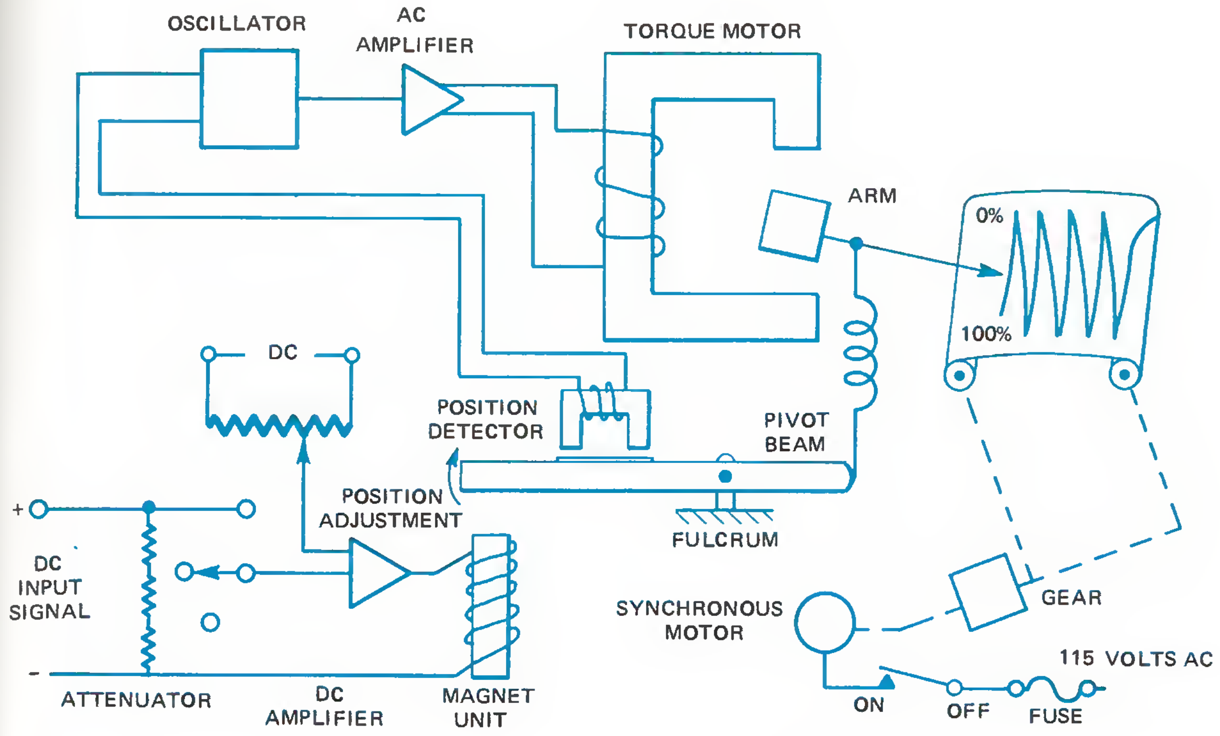


Fig. 11-6 Force-Balance Recorder

tioning adjustment is set so that the current through the coil of the magnetic unit is sufficient to produce a magnetic field which balances the beam at a point where the pen is at the lowest end (0%) of the chart. When a DC signal is applied to the input, the current is amplified by the DC amplifier. The increase in current through the magnetic unit unbalances the beam. As a result, the arm moves upward.

The stronger the input signal, the more the arm is moved upward. As the beam is deflected, the air gap of the position detector is decreased. As the air gap is decreased, the inductance of the coil of the position detector is increased. Since this coil is a component of the oscillator, the output current is increased. The output of the oscillator is coupled to an AC amplifier, which drives a torque motor. The torque moves the arm and pen up toward the upper end (100%) of the chart. As the torque motor drives the arm up, the force in the spring is increased. When the CCW moment produced by the spring is equal to the CW moment produced by the magnetic unit, the beam balance is restored.

The torque motor produces a rotary mechanical force proportional to the current flowing through its coil. A soft-iron armature is pivoted within the air gap of the horseshoe-shaped frame. A coil is wound on the frame. As the current through the coil is increased, the magnetic field is increased and tends to force the armature to line up across the air gap. The rotation caused by the increase in the magnetic field is opposed by a spring attached to its arm. Thus, the position of the arm is dependent upon the signal strength. The rotation of the armature is limited to a few degrees.

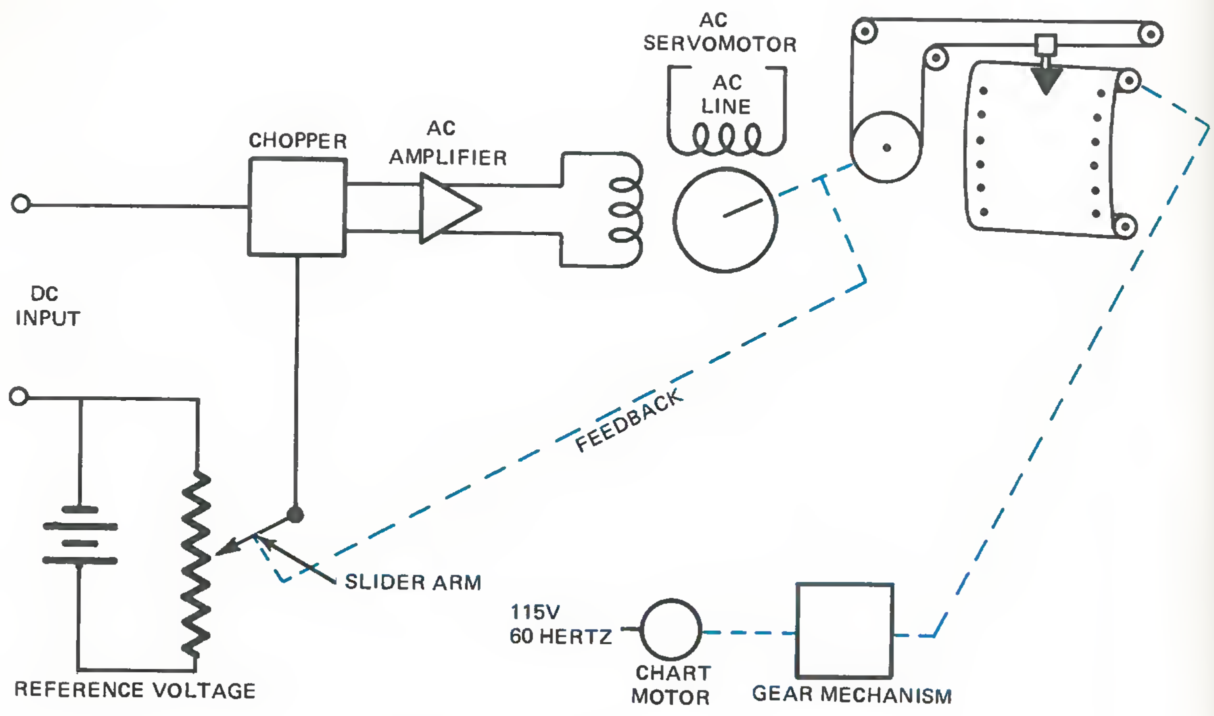


Fig. 11-7 Null Balance Type Recorder

The null-balance type recorder is shown in figure 11-7. This recorder is an automatic control system used to position an arm. This type recorder may be designed to respond to a DC input signal, AC input signal, resistance input or a combination of the three. The measuring unit of the amplifier may be a differential transformer, resistance bridge, or a potentiometer circuit with chopper and amplifier. When a DC signal voltage is applied to the input of the recorder, it is compared with the reference voltage and a DC error voltage is generated.

This error voltage is applied to the chopper which converts it to a corresponding AC error signal. The AC error signal is amplified to a sufficient level to drive the servomotor. The shaft of this motor is coupled to the slider arm of the balancing mechanism and to the pen arm. The servomotor drives the pen arm and the slider arm until the error voltage to the chopper is zero (null-balance). A positioning circuit (not shown) is used to set the pen trace to zero or a convenient reference point. To use this type recorder as a X-Y recorder, another channel is added to drive the pen in the vertical direction. The chart paper remains stationary for this type operation. An X-Y recorder is shown in figure 11-8.

Where the input signal is pneumatic, the recorder used is called a pneumatic recorder.

The measuring unit of this recorder is a pressure-to-motion transducer. The transducer may be a Bourdon tube, a bellows or a diaphragm. The resulting motion produced by a change in pressure is linked to the pen arm through gears, belts, springs and other mechanical devices. A pneumatic recorder using the spiral Bourdon tube as the measuring unit is shown in figure 11-9.

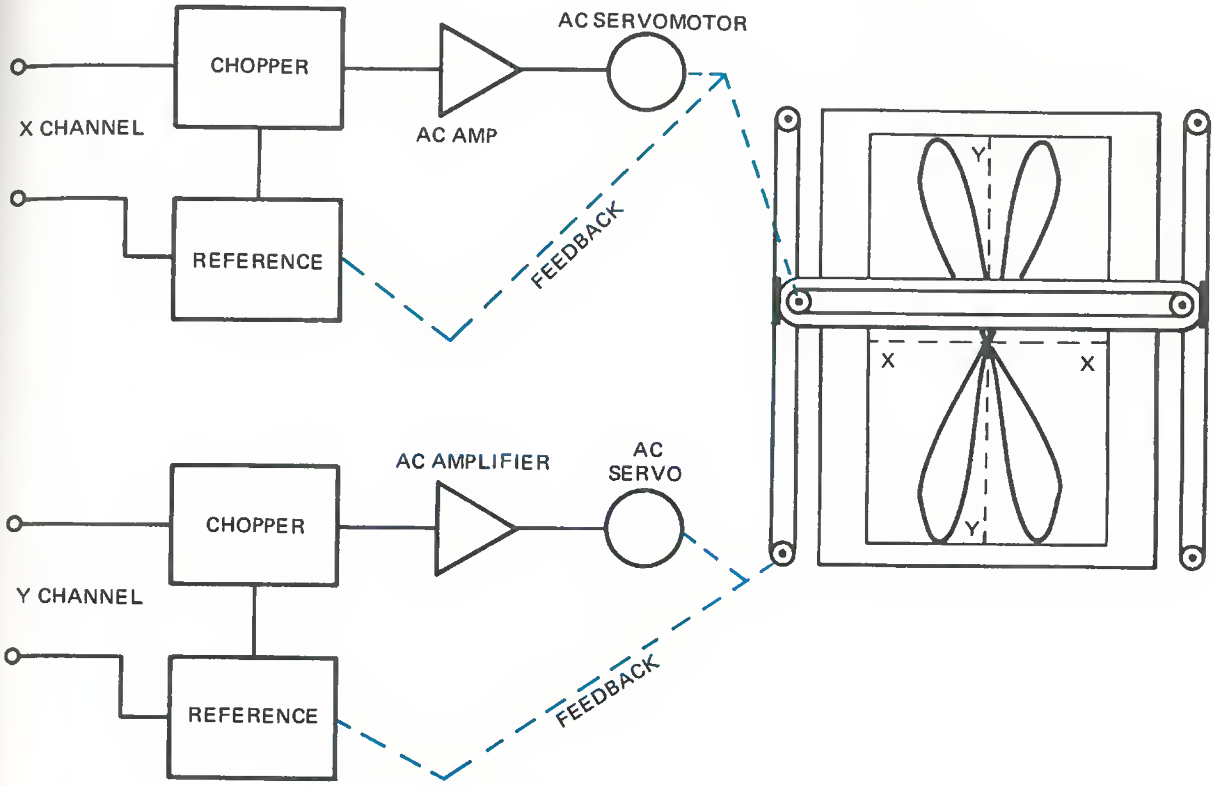


Fig. 11-8 X-Y Recorder

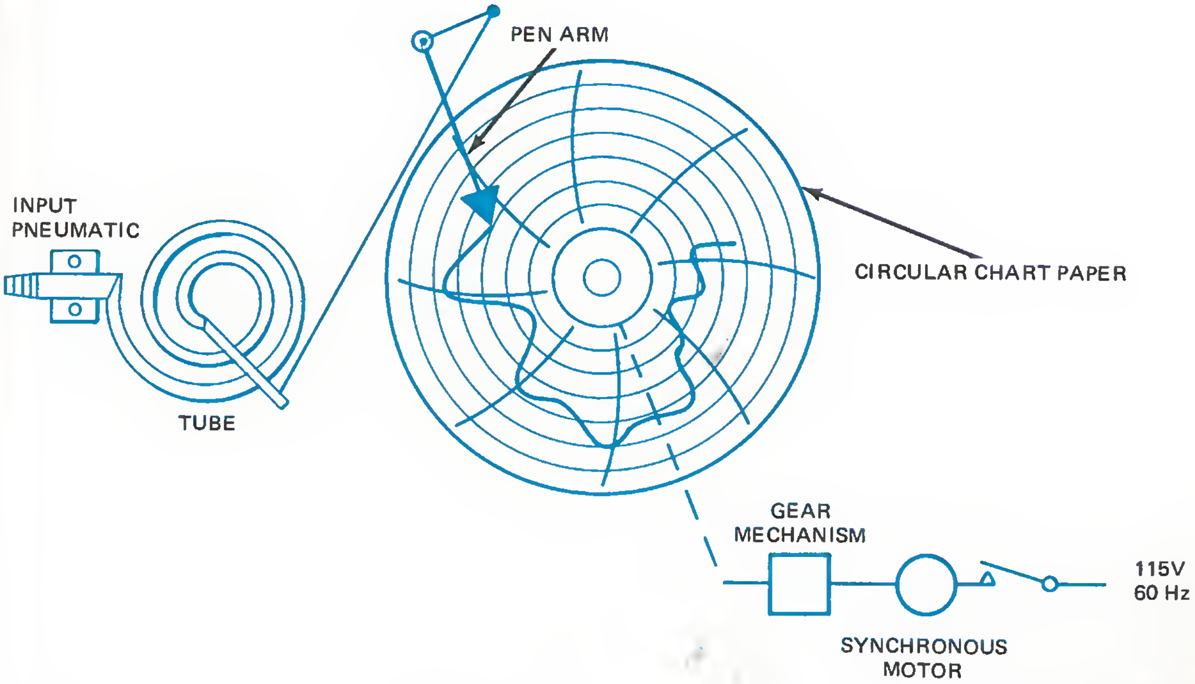
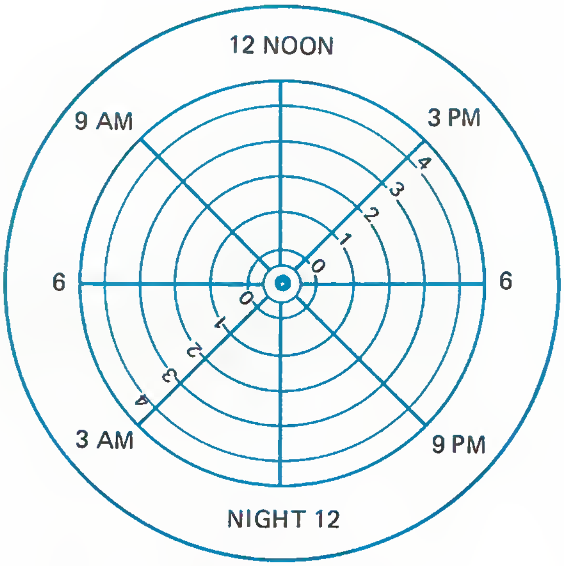
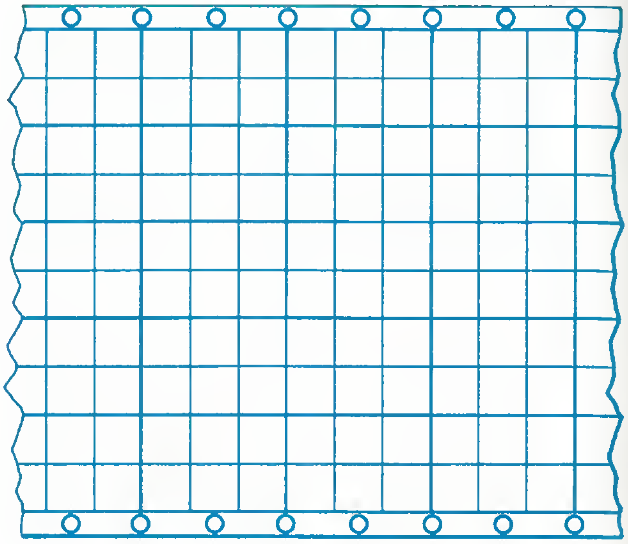


Fig. 11-9 Pneumatic Recorder



24 HOUR
CIRCULAR CHART



STRIP CHART

Fig. 11-10 Chart Forms

The type of recording medium depends on the recording device used. Generally, the recording devices are pen and ink, light beams called oscillographs, electric stylus, thermal stylus and magnetic heads. The mediums used for the recording devices are paper charts, photosensitive paper or films, paper coated with zinc or aluminum, paper coated with wax or special oxide that is thermal sensitive, and magnetic tape, respectively.

The recording medium may be in circular form, called a circular chart, a strip of roller paper, called a strip chart, or magnetic tape or drum. The circular chart and the strip chart are shown in figure 11-10.

Chart drives for circular charts and strip charts are synchronous motors, spring motors and motor-driven wound springs. Chart speed variations are accomplished by heat mechanisms and variable speed motors. Strip charts are more complicated than circular charts as they must include a supply reel and a take-up reel drive. Strip charts may be driven by a sprocket meshing with holes in the edge of the paper or by the reel itself.

Counting indicators are often employed in industry. Counters generally are divided into three types: mechanical, electrical and electronic. The mechanical counter or register consists of a set of wheels coupled together through a 10 to 1 reducing gear. The edge of each wheel is divided into ten equal parts and each part is numbered 0 to 9. These numbers appear at a window in the face of a counter. The count mechanism is actuated either by a stroke arm or a rotary shaft. A mechanical counter is shown in figure 11-11.

The electrical counter resembles the stroke register except the unit's wheel is actuated by an electromagnet. If a solenoid mechanism were used to actuate the unit's wheel for each pulse of current flowing through the magnet coil, the unit would be considered an electrical counter. Mechanical

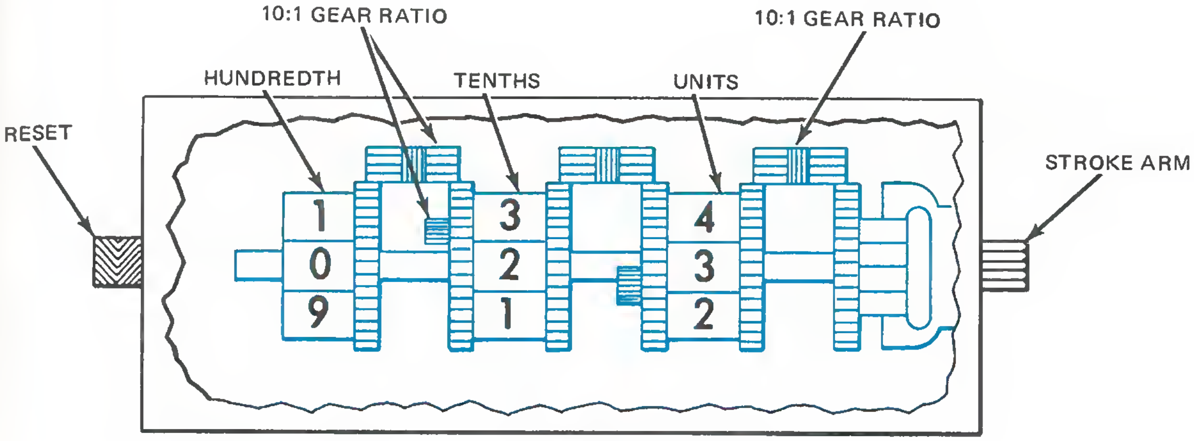


Fig. 11-11 Mechanical Counter

and electrical counters are available that count up to about 10,000 counts per minute.

Where very fast counting is desired, the electronic counter is used. Binary counters and decade counters using bistable multivibrators (flip-flops) and glow transfer tubes are employed in electronic counters.

For time measurement, clock timers and electronic timers are used as the measuring unit. The clock timer may be a mechanical device much like a windup alarm clock. Electrical timers usually use a synchronous motor. Electronic timers operate on a principle involving the time constant of a resistance-capacitance circuit.

MATERIALS

- 1 Torque receiver, type 23TR6 or equivalent
- 1 Torque transmitter, type 23TX6 or equivalent
- 1 Pointer and dial assembly
- 1 Test stand
- 1 AC voltmeter
- 1 Oscilloscope
- 1 Variable transformer

PROCEDURE

1. Construct the experimental circuit shown in figure 11–12.
2. Connect an AC voltmeter between terminals S_1 and S_3 of the *torque transmitter.*
3. Rotate the synchro rotor until the voltmeter reads approximately zero. The synchro si now 0° or 180°.
4. Remove the voltmeter from the circuit, connect S_3 to R_2 and connect the voltmeter between S_2 and R_1.
5. If the meter reads more than the line voltage, rotate the rotor 180° and repeat steps 2, 3 and 4. If the meter reads less than the line voltage, proceed with the next step.
6. Remove the voltmeter from the circuit, disconnect S_3 from R_2 and connect the voltmeter between S_1 and S_2.

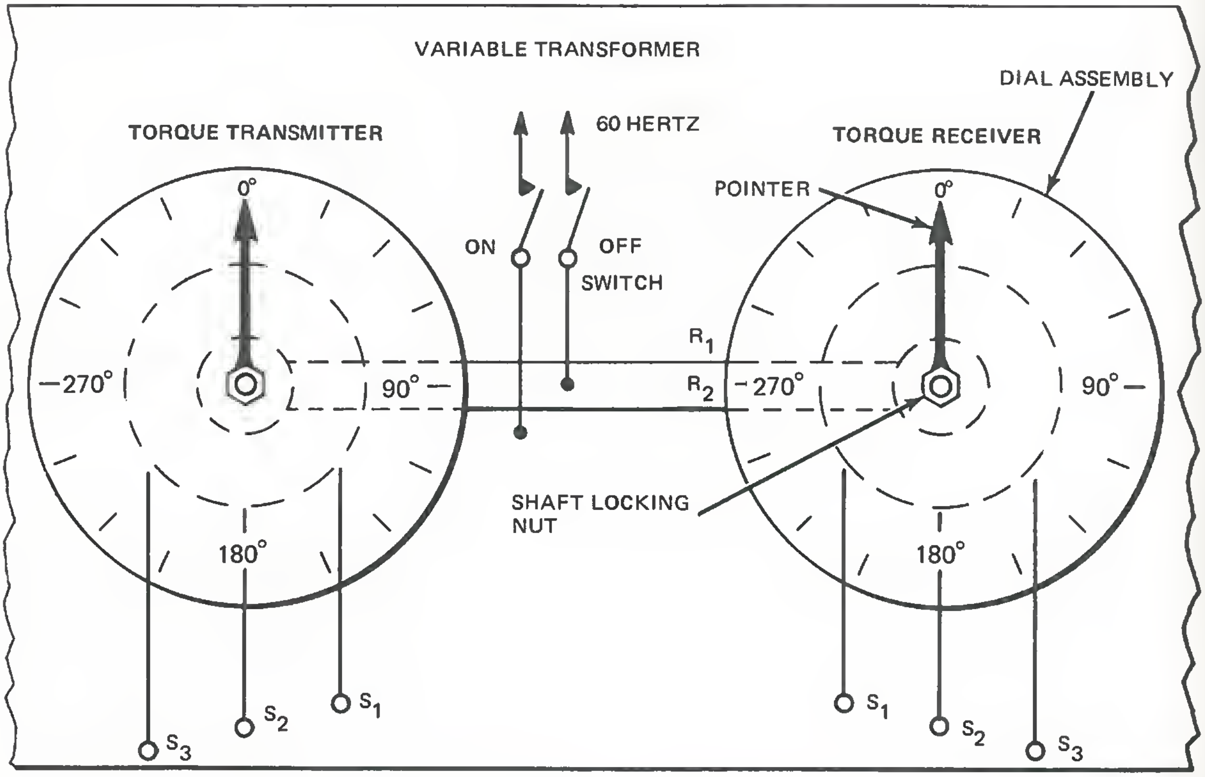


Fig. 11-12 Remote Indication Test Circuit

7. Very carefully, rotate the synchro rotor until the voltmeter reads zero on the lower scale.
8. Without disturbing the rotor position, adjust the pointer to zero degrees on the dial assembly, and secure the pointer to the rotor shaft. This completes zeroing of the torque transmitter.
9. Connect S_2 of the synchro torque receiver to R_1 and connect jumper S_1 and S_3 to R_2.
10. The receiver will set itself to electrical zero.
11. Very carefully, without disturbing the synchro rotor position, adjust the pointer to zero. This completes zeroing the torque receiver. Do not leave the synchro connected to the line longer than necessary.
12. Connect the stator leads of the transmitter to the stator leads of the receiver.
13. Rotate the rotor of the torque transmitter (CW and CCW) and observe the operation of the torque receiver. Record the observed operation.
14. Connect S_1 of the torque receiver to S_3 of the torque transmitter, and S_3 of the torque receiver to S_1 of the torque transmitter.
15. Repeat step 13.

16. Connect R_1 of the torque receiver to R_2 of the torque transmitter, and R_2 of the torque receiver to R_1 of the torque transmitter and connect the rotors to 115 volts, 60 Hertz.
17. Connect S_1 of the torque receiver to S_1 of the torque transmitter, and S_3 of the torque receiver to S_3 of the torque transmitter.
18. Repeat step 13.

ANALYSIS GUIDE. Discuss the operation of the remote indicator system based on the observation made in the experiment. Relate how you could determine if the rotor leads of either the synchro transmitter or receiver were reversed. Relate how you could determine if the stator leads S_1 and S_3 are connected in reverse. Why is it necessary to perform the zeroing operation?

Step 13: Receiver Action____

____

Step 15:____

____

____

Step 18:____

____

Fig. 11-13 The Observed Results

PROBLEMS

1. Define a telemetry system.
2. Discuss each of the static and dynamic characteristics of an instrument.
3. Draw a diagram of a test setup using the strip chart recorder to monitor the controlled variable of a temperature chamber (at 212°F) over a period of 4 hours. Use a thermocouple detector whose output is rated a 1 mV per 50°C. A DC amplifier with a gain of 1000 is used between the moving coil recorder and the thermocouple detector.
4. What type of recorder could you use to automatically plot voltage versus current? Show how the test circuit would be set up.

experiment 12 SYSTEM RESPONSE

INTRODUCTION. The frequency response of a control system is very important in any practical situation. In this experiment, the system response of automatic control systems will be examined.

DISCUSSION. In order to analyze an automatic control system, it is helpful to use a block diagram. An open-loop, single-stage voltage amplifier block diagram is shown in figure 12-1A. The relationship between the output function of a system to its input is called a *transfer function.* The transfer function of the amplifier in the figure may be given as

$$\boxed{\text{Transfer function} = \frac{\text{output}}{\text{input}} = \frac{E_{out}}{E_{in}} = -A_u} \tag{12.1}$$

For a two-stage amplifier, such as the one shown in figure 12-1B, the system transfer function will be

$$\text{Transfer function} = \frac{E_{out}}{E_{in}} = A_1 A_2$$

Thus, if two blocks are in series, the system transfer function is the product of the individual transfer functions. Every mechanical, electrical, fluid or thermal system has a transfer function. The transfer function of the series resistance circuit shown in figure 12-1C is

$$E_o = \frac{E_{in}R_2}{R_1 + R_2}$$

The output of a summing device or point is the algebraic sum of its input. The block diagram of a summing circuit is shown in figure 12-2. The output of the circuit may be determined as

$$E_o = E_1 \pm E_2 \tag{12.2}$$

The block diagram of an amplifier with feedback is shown in figure 12-3. A is the gain of the amplifier and B is the feedback (B is negative if negative feedback is used, and positive if positive feedback is employed). The transfer function of this system will be

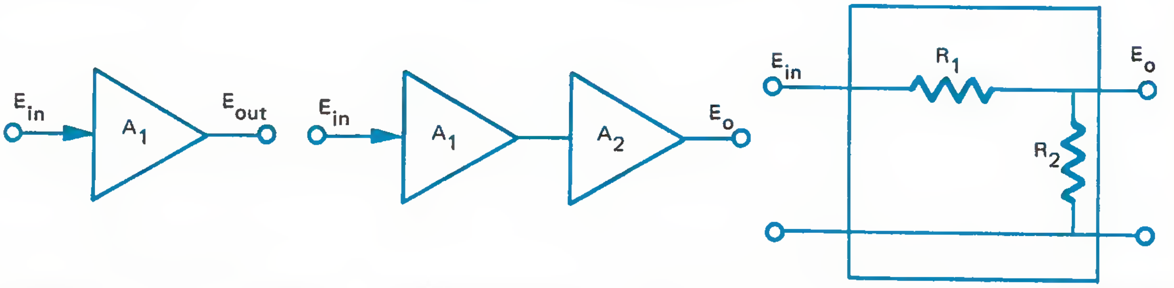
$$E_o = (E_{in} - \beta E_o)(-A)$$

$$E_o = AE_{in} + A\beta E_o$$

$$E_o - A\beta E_o = -AE_{in}$$

$$E_o\,(1 - A\beta) = -AE_{in}$$

$$\boxed{\text{Transfer function}\ \frac{E_o}{E_{in}} = \frac{-A}{(1 - A\beta)}} \tag{12.3}$$



(A) AMPLIFIER, SINGLE STAGE *(B) AMPLIFIER, TWO STAGE* *(C) SERIES RESISTANCE NETWORK*

Fig. 12-1 Block Diagram

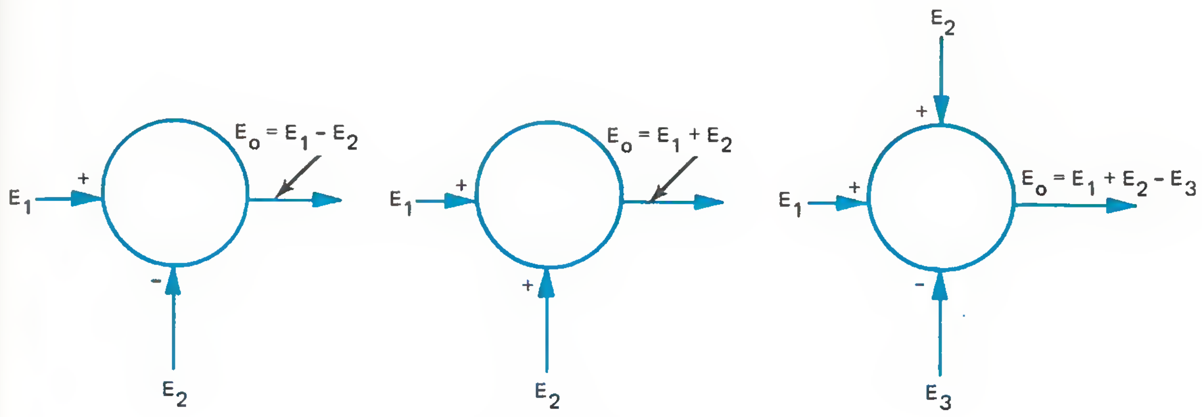


Fig. 12-2 Summing Devices

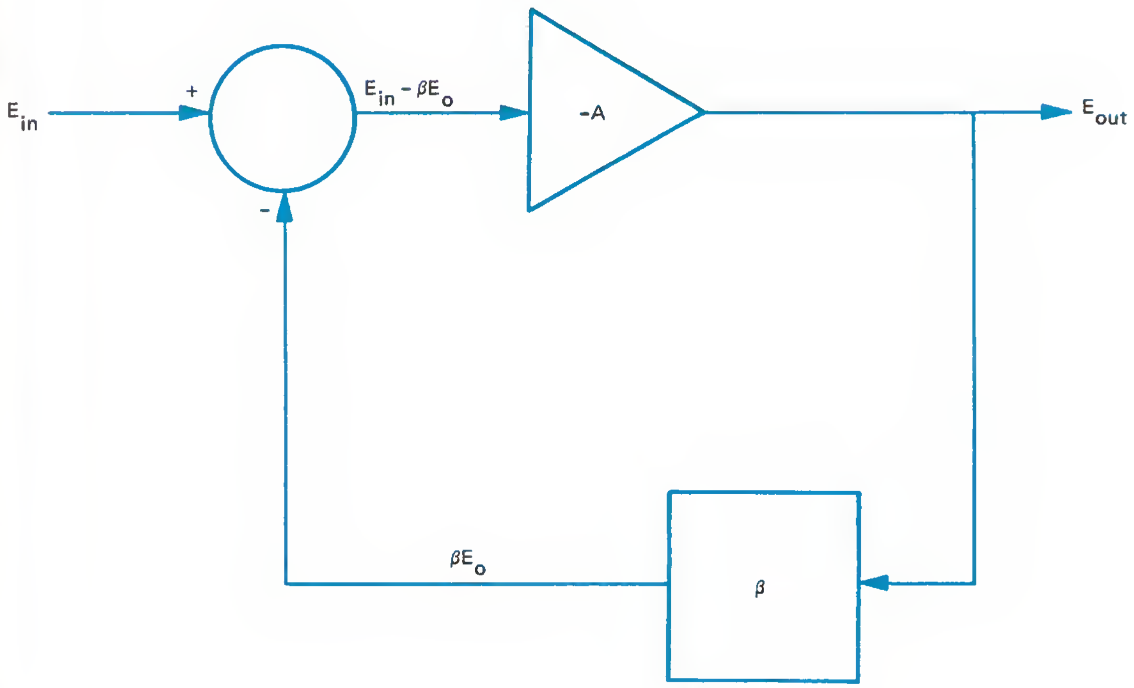


Fig. 12-3 Feedback Amplifier Block Diagram

One problem of process control originates with the necessity of minimizing the effect of changes in the controlled variable. The process or system and the controller, acting together, comprise the controlled system, and the characteristics of the process as well as the characteristics of the controller affect the performance of the complete system. To determine the characteristics (transfer function) of a complete system, it is necessary to determine the transfer function of each block contained in the system block diagram. An automatic control system block diagram is shown in figure 12-4.

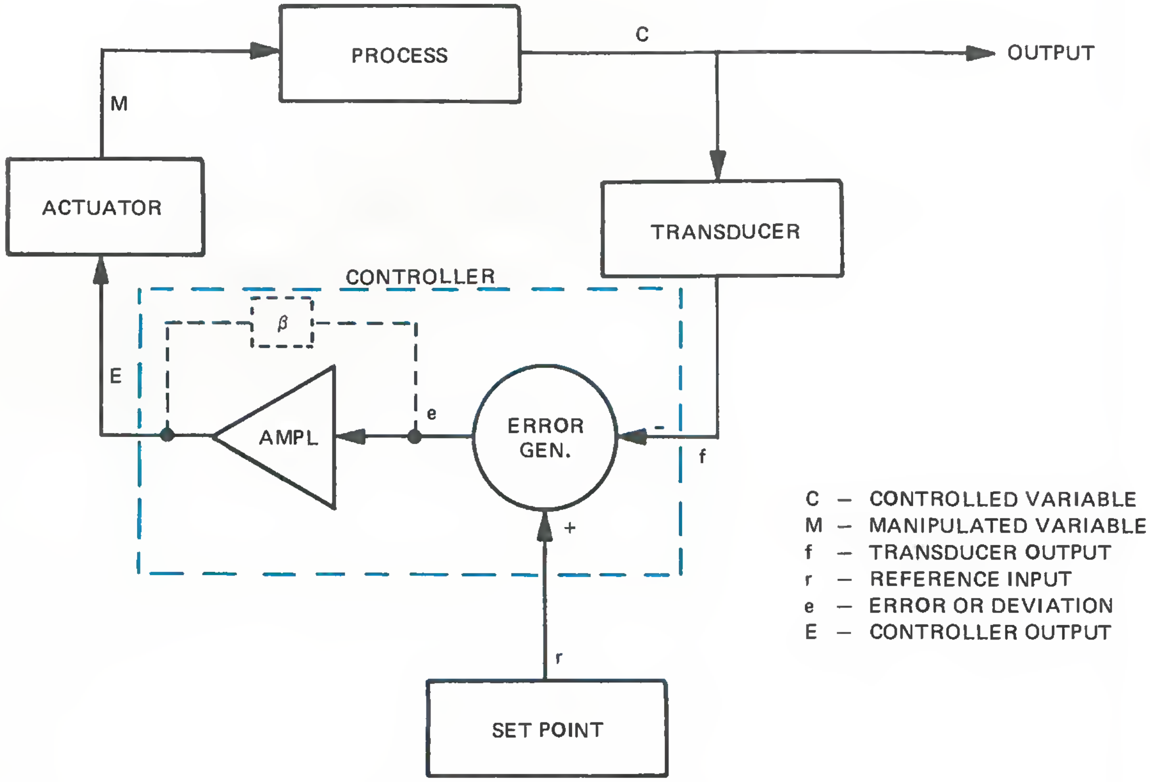


Fig. 12-4 Automatic Control System Block Diagram

The output (f) of the transducer depends on its input (C) and the sensitivity (K_T) of the transducer. The gain of a transducer may be determined by dividing the change in output by the amount of change in the input. Then the gain may be stated mathematically as

$$K_T = \frac{\Delta f}{\Delta C} \qquad (12.4)$$

Therefore, the output of the transducer will be

$$f = K_T C \qquad (12.5)$$

Let's consider a tachometer generator which produces an output voltage of 100 volts at 5,000 RPM. We can determine the transducer sensitivity,

$$K_T = \frac{\Delta f}{\Delta C} = \frac{100 \text{ volts}}{5000 \text{ RPM}} = 0.02 \text{ volts/RPM}$$

and we can determine the transducer output when the controlled variable is 1000 RPM.

$$f = K_T C = 0.02 \text{ volt/RPM} \times 1000 \text{ RPM}$$

$$= 20 \text{ volts}$$

A control system usually requires a steady value set-point that is identical to the reference input r, and is expressed in the same units as the transducer output.

The error signal (e) applied to the input of a controller amplifier may be determined using

$$e = r - f \qquad (12.6)$$

For example, if the transducer output above is 20 volts and the reference voltage input is 19 volts, the error signal voltage will be

$$e = r - f$$

$$e = 19 - 20 = -1 \text{ volts}$$

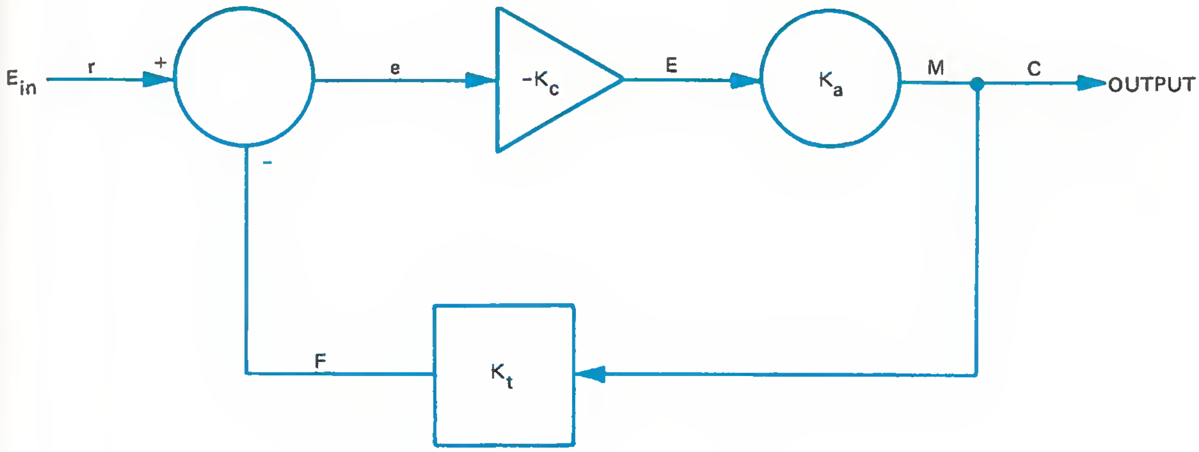


Fig. 12-5 A Linear Automatic Control System

The output of a linear controller depends on the error voltage input and the gain, K_c, of the controller. The gain of the controller amplifier will be

$$K_c = \frac{\Delta E}{\Delta e} \qquad (12.7)$$

Therefore, the output of the controller is

$$E = K_c e \qquad (12.8)$$

So, we determine that the output of a controller that has a sensitivity of 10 and an input of 3 lbs is

$$E = K_c e = 10(3) = 30 \text{ lbs}$$

The actuator of a control system is usually a linear element. A linear element is an element whose output is proportional to its input. The actuator output (the manipulated variable M) is proportional to the output of the controller, and the sensitivity of the actuator is

$$K_a = \frac{\Delta M}{\Delta E} \qquad (12.9)$$

Consequently, the output of the actuator (the manipulated variable) may be determined by

$$M = K_a E \qquad (12.10)$$

Now we can determine the transfer function of the whole system. The block diagram of figure 12-4 can be redrawn as shown in figure 12-5.

The system transfer function may be found as follows:

$$C = M = E(K_a)$$

$$M = EK_a = e(-K_c)\,K_a$$

$$M = (r - f)\,(-K_c)\,(K_a)$$

The system equation is:

$$M = -K_cK_ar + K_cK_af$$

$$M = -K_cK_ar + K_cK_aK_tM$$

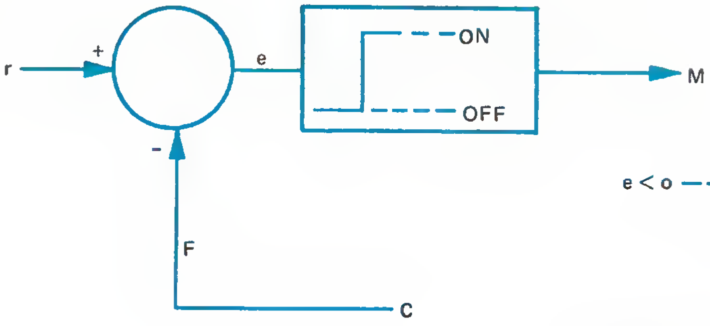
$$M - K_cK_aK_tM = -K_cK_ar$$

$$M(1 - K_cK_aK_t) = K_cK_ar$$

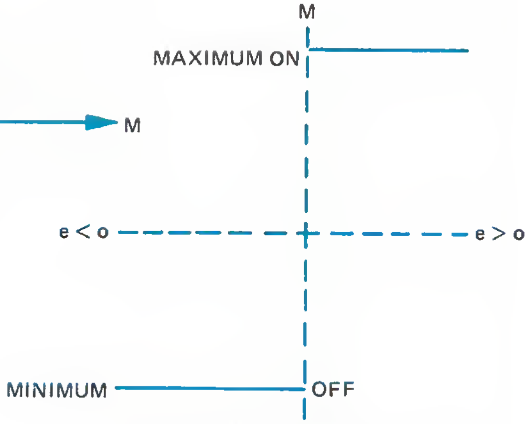
$$\frac{M}{r} = \frac{K_cK_a}{1 - K_t(K_cK_a)}$$

$$\boxed{\text{System transfer function} = \frac{K_cK_a}{1 - K_t(K_cK_a)}} \qquad (12.11)$$

Compare this equation with equation 12.3. Notice that K_cK_a is the open-loop gain and K_t is the feedback constant.



(A) BLOCK DIAGRAM



(B) RESPONSE OF MANIPULATED VARIABLE TO A STEP IN ERROR

Fig. 12-6 Two-Position Control

The transfer function of a two-position control system, on-off control, must be described by two equations, each applying in a certain region of operation. The block diagram may be constructed as shown in figure 12-6. The equations for the two positions are

$$M = \text{Maximum (on)}\ e > 0$$

$$M = \text{Minimum (off)}\ e < 0 \qquad (12.12)$$

From equation 12.12, if the error is zero or less, the manipulated variable is at a minimum (off), and if the error is greater than zero, the manipulated variable is at a maximum (on).

In a proportional control system, the controller amplifier gain is a linear function of its input error signal. The block diagram of this system is shown in figure 12-7. The system's transfer function may be determined as follows:

$$C = M = K_aE$$

$$M = K_a(-K_ce)$$

$$\frac{\text{System}}{\text{equation}} = \quad M = K_a[-K_c(r - f)]$$

$$M = K_a[-K_c(r - K_tM)] \qquad (12.13)$$

$$M = K_a[-K_cr + K_cK_tM]$$

$$M = -K_aK_cr + K_aK_cK_tM$$

$$M - K_aK_cK_tM = -K_aK_cr$$

$$\text{Transfer function} = \frac{m}{r} = \frac{-K_aK_c}{1 - K_aK_cK_t} \qquad (12.14)$$

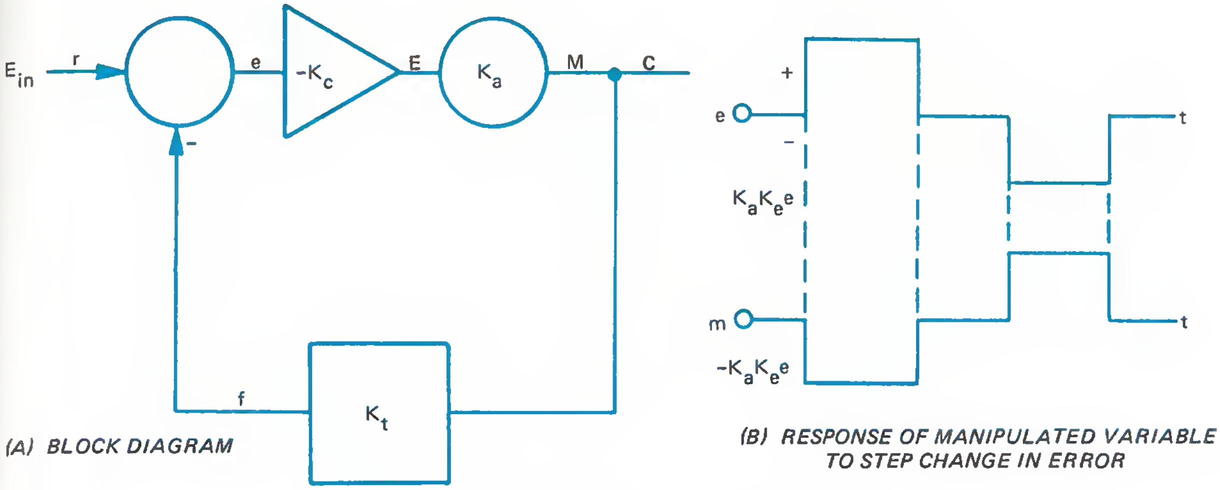
From equation 12.13, if the deviation or error is zero ($r = f$), the controlled variable is at the desired value and the manipulated variable is zero.

$$M = K_a[-K_c(r - f)]$$

$$M = K_a[-K_c(0)]$$

$$M = 0$$

If the set-point value is greater than the transducer output ($r > f$), the controlled variable is less than the desired value, and the manipulated variable must be increased by the actuator. The actuator will drive the manipulated variable until the controlled variable is at the desired operating value.



(A) BLOCK DIAGRAM

(B) RESPONSE OF MANIPULATED VARIABLE TO STEP CHANGE IN ERROR

Fig. 12-7 Proportional Control System

$$M = K_a[-K_c(r - f)]$$

$$M = -K_aK_c(+e)$$

If the set-point value is less than the transducer output ($f > r$), the controlled variable is greater than the desired value, and the manipulated variable must be decreased by the actuator. The actuator will drive the manipulated variable until the controlled variable is at the desired operating value.

$$M = K_a[-K_c(r - f)]$$

$$M = -K_aK_c(-e)$$

$$M = K_aK_ce$$

The change in the manipulated variable corresponds to the change in derivation with a given value of amplification. The value of amplification depends on the proportional sensitivity (K_c) of the controller. Generally, the sensitivity of the controller is adjustable.

For example, a certain control system has an amplifier with a gain of –10, a transducer sensitivity of 1 volt/RPM, and an actuator gain of 100 RPM/volt. Let's determine the desired value of the controlled variable when the set-point is 5 volts. Assume the controlled variable is identical to manipulated variable

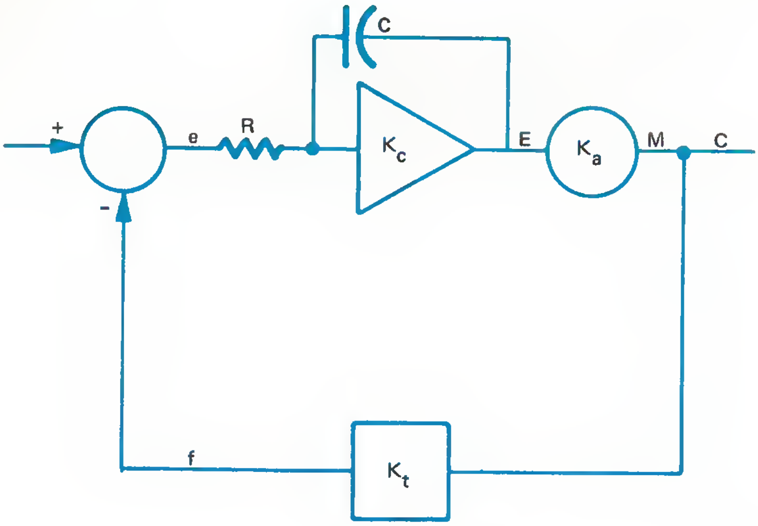
$$\frac{M}{r} = \frac{K_aK_c}{1 - K_aK_cK_t}$$

$$C = M = \frac{-rK_aK_c}{1 - K_aK_cK_t}$$

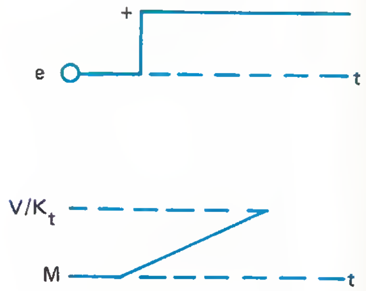
$$C = \frac{-5 \text{ volts } 100 \text{ RPM/volt } (-10)}{1 - 100 \text{ RPM/volt } (-10) \text{ volts/RPM}}$$

$$= 5 \text{ RPM}$$

Proportional control is the simplest closed-loop system in automatic control. Since the controller transmits to the actuator a signal that is directly proportional to the magnitude of the signal from the transducer, the ratio of the percentage of full scale output of the transducer to the percentage of full scale output from the controller is called the proportional band. The smaller the proportional band, the greater the proportional sensitivity, and the more precise the control of the process. Processes controlled only by a proportional control will have a small difference between the controller set-point and the controlled variable. This difference is called off-



(A) BLOCK DIAGRAM



(B) RESPONSE OF MANIPULATED VARIABLE TO A STEP CHANGE IN ERROR

Fig. 12-8 Integral Control System

set. Reducing the proportional band can reduce the offset, but this increases the sensitivity, and if carried too far, the system will become unstable and oscillate. The oscillations cause continuous movement of the actuator (hunting). To reduce the offset resulting from proportional control, reset action (integral action) can be added to the system.

The effect of dead time, a definite delay between two related actions, in proportional control requires the sensitivity to be reduced (increasing the proportional band) in order to maintain stability. Even a small dead time can cause serious consequences in a proportional control. To reduce the effect of dead time, rate action (derivative action) can be added to the system.

In an integral control system, the manipulated variable is changed at a rate proportional to the deviation. The block diagram for this type of system is shown in figure 12-8. The system transfer function may be determined as follows:

$$C = M = K_a E$$

But for integral control,

$$E = \frac{1}{T_i}\int e\,dt$$

where T_i is the integral time. Therefore,

$$M = \frac{K_a}{T_i}\int e\,dt$$

Differentiating,

$$dM = \frac{K_a}{T_i} e\,dt \tag{12.15}$$

or

$$dM = \frac{K_a}{T_i}(r - f)\,dt$$

System equation:

$$dM = \frac{K_a}{T_i}(r - K_t M)\,dt \tag{12.16}$$

For a step input:

$$\frac{dM}{(r - K_tM)} = \frac{K_a}{T_i}dt$$

$$\int_0^M \frac{dM}{(r - K_tM)} = \frac{K_a}{T_i}\int_0^t dt$$

$$\frac{K_a}{T_i}t = \frac{1}{K_t}\ell n\,(r - K_tM\Big|_0^M$$

$$\frac{K_a}{T_i}t = \frac{1}{K_t}\ell n\, r - \frac{1}{K_t}\ell n\,(r - K_tM)$$

$$\frac{K_tK_a}{T_i}t = \ell n\, r - \ell n\,(r - K_tM)$$

$$\frac{K_tK_a}{T_i}t = \ell n\,\frac{r}{(r - K_tM)}$$

Taking the antilogarithm of each side,

$$\text{antilogarithm}\,\frac{K_tK_a}{T_i}t =$$

$$= \text{antilogarithm}\,\ell n\left(\frac{r}{(r - K_tM)}\right)$$

$$e^{K_tK_at/ti} = \frac{r}{r - K_tM}$$

$$\frac{1}{e^{-K_tK_at/ti}} = \frac{r}{r - K_tM}$$

Transfer function for step input:

$$\frac{M}{r} = \frac{1}{K_t}\left(1 - e^{-K_tK_at/T_i}\right)$$

In the integral control system, the actuator is moved twice as fast when the deviation or error is doubled over a previous value. When the controlled variable is at the set-point (zero error), the actuator element is stationary. Thus, the manipulated variable changes with time and integrates the area under the error curve. The integral time (T_I) is defined as the time of change of the manipulated variable caused by a unit change in error.

As an example, let's consider an integral pneumatic control system. A zero deviation causes the actuator piston to be at the middle of its 10-inch stroke. The integral time is 0.2 sec. Let's calculate the rate of piston motion when the deviation changes suddenly by 1 inch if the actuator gain (K_a) is 10.

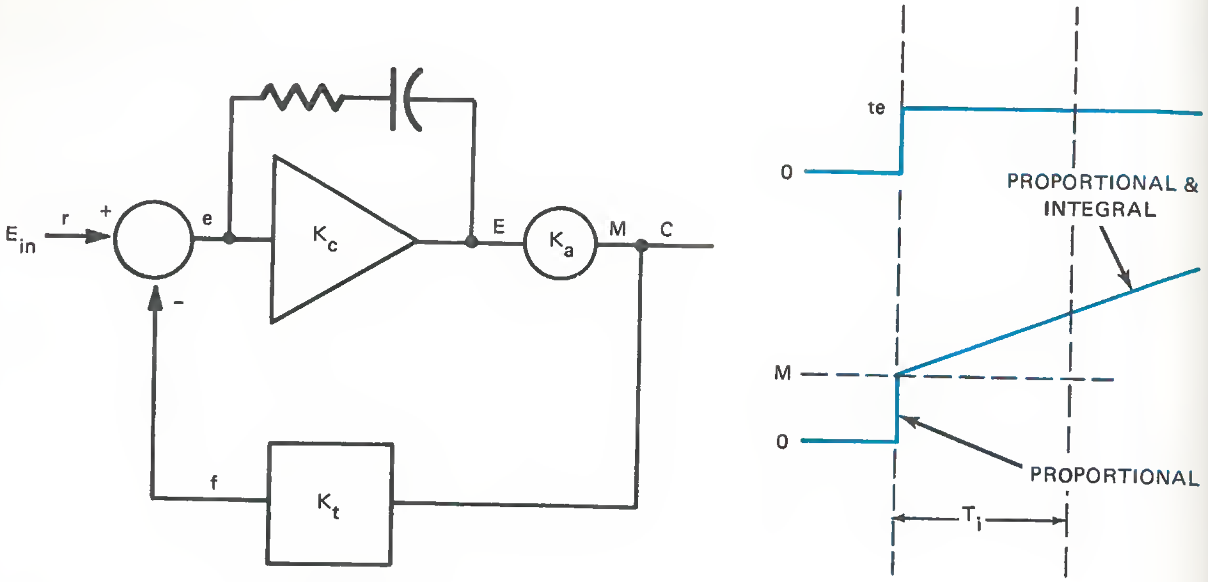
$$\frac{dM}{dt} = \frac{K_a}{T_i}e\,dt$$

$$\frac{dM}{dt} = \frac{10\text{ in.}}{0.2\text{ sec}} = 50\text{ in./sec}$$

Notice that the actuator gain (K_a) is included in dM/dt in this example.

Integral control is usually employed for control of fluid flow, liquid level and pressure, as well as in processes having little or no energy storage. The characteristics of integral control help reduce offset, because the integral action forces the system to return to the set-point when there is a change in load. The integral system will not operate satisfactorily with any dead time present. If dead time is present, the system will become unstable and begin to oscillate severely. The integral time of the controller must be selected to provide the proper *damping* with minimum deviation and without excessive oscillation.

A proportional-integral control system combines proportional action with integral control action to obtain the advantage of stability of the proportional control and reduction of offset by integral control. This type of control is the most widely used of all types of control. The block diagram for a proportional-integral control system is shown in figure 12-9.



(A) BLOCK DIAGRAM

(B) RESPONSE OF MANIPULATED VARIABLE TO STEP CHANGE IN ERROR

Fig. 12-9 Integral Control

The system equation may be determined as follows:

$$C = M = K_a E$$

But, for combined proportional integral control,

$$E = \frac{K_c}{T_i}\int e\,dt + K_c e$$

where T_i is the integral time. Therefore,

$$M = \frac{K_a K_c}{T_i}\int e\,dt + K_a K_c e \qquad (12.19)$$

Differentiating,

$$dM = \frac{K_a K_c}{t_i} e + K_a K_c \frac{de}{dt}$$

System equations

$$= dM \frac{K_a K_c}{T_i}(r - f) + K_a K_c \frac{d(r - f)}{dt}$$

(12.20)

Proportional-integral control usually has two adjustments: K_c, the sensitivity, and T_i, the integral time. For a step change in deviation, the integral time is the time required to add an increment of response equal to the original step change of response. Reset-rate is defined as the number of times per minute that the proportional part of the response is repeated. Reset-rate is expressed in "repeats per minute" and is the inverse of integral time.

Proportional-integral control may be utilized for any process that requires the use of either of its two types of response. The disadvantages of this type control are the excessive stabilization time required when the process has many energy storage elements.

Derivative control action can be added to proportional control in systems having a very large number of storage elements, and for control systems having troublesome dead time. Derivative action allows the proportional sen-

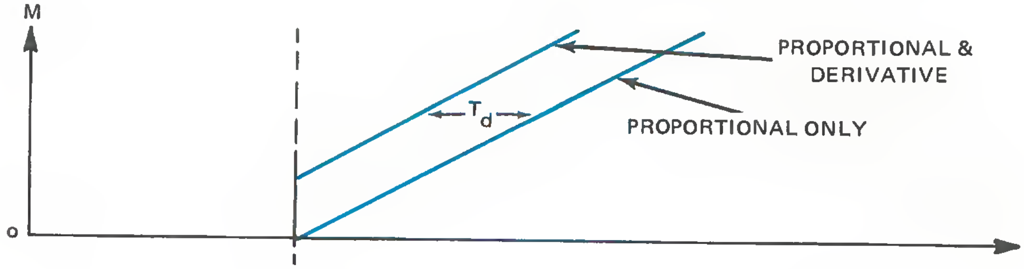


Fig. 12-10 Derivative Time for a Step Input in Deviation

sitivity to be increased without excessive oscillation. The increased sensitivity reduces offset. When the derivative control is used with proportional-integral action, the integral time can be reduced. The system equations for a system containing derivative action are:

For proportional plus derivative action:

$$M = K_aK_ce + K_aK_cT_d\, de/dt \qquad (12.21)$$

For proportional plus derivative plus integral:

$$M = K_aK_ce + K_aK_cT_d + \frac{K_aK_c}{T_i}\int e\,dt \qquad (12.22)$$

The time, T_d, is the derivative time. Derivative time is defined as the amount of lead that the control action is given, and it is the time integral by which the rate action advances the effect of proportional control. This effect is shown in figure 12-10.

The transfer function or system equation can be used to obtain the response time and the frequency response of an automatic control system.

The response time is the time it takes the system to correct the controlled variable when an error is initiated. The response time of a system is a function of the actuator speed, dead time, offset, the storage elements in the system and of the dead band.

The dead band is the range through which an input can be varied without initiating a response. The dead band is a function of the actuator sensitivity and the amplifier gain. As an example, consider a TX and TR connected as a remote indicator. The number of degrees on both sides of electrical zero (or any other position) that the control transmitter shaft can be rotated without initiating a response output of the control receiver is called the dead band. A dead band of 2° for such a system is shown in figure 12-11.

After the system moves out of the dead band, the primary response factor is a function of the actuator speed. The first speed response factor is the velocity error coefficient or velocity lag error. Velocity error results when the set-point is a steadily changing quantity, and the controlled variable, in an attempt to follow the input, lags behind with a steady deviation. The second speed of response factor is the rise time. The rise time is the time it

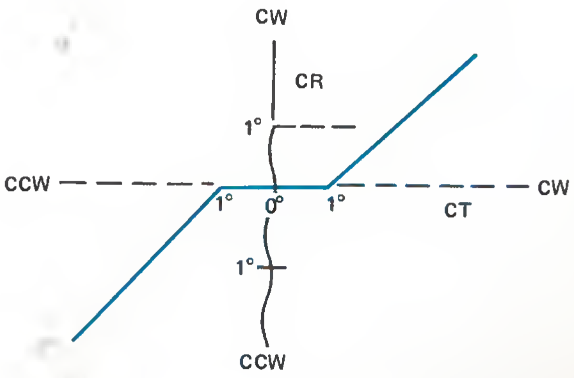


Fig. 12-11 Dead Band of a Synchro System

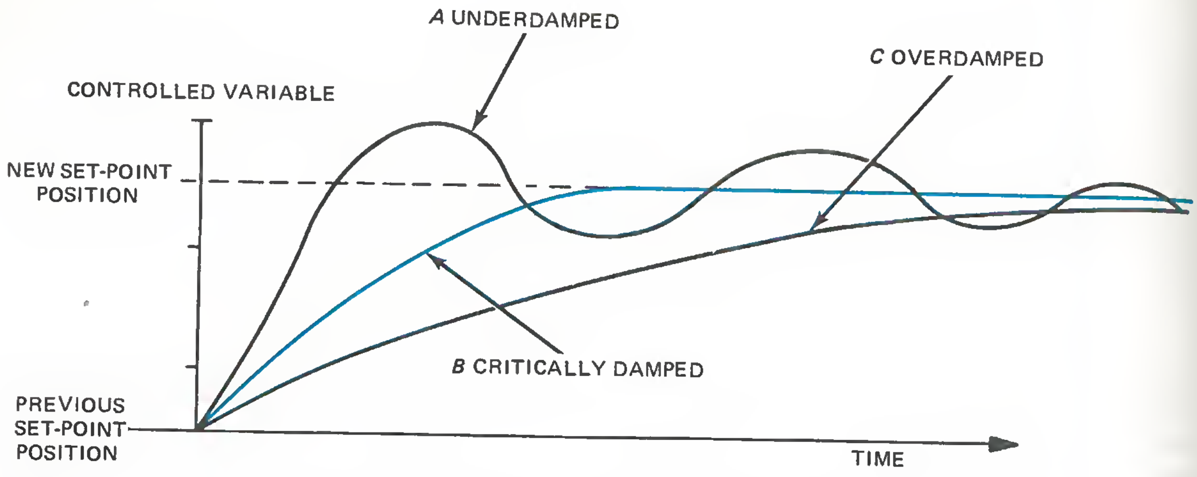


Fig. 12-12 Effect of Damping on Response Time

takes the controlled variable to travel from 10% to 90% of its final value. The third factor is the settling time. In any process control system, the controlled variable may overshoot the desired value and oscillate (hunt) about this value before settling down.

Hunting may be reduced by employing a damping device, decreasing the gain of the controller amplifier, or compensating for the time delay within the controlling device. The use of mechanical dampers requires more power and increases the velocity error. Increasing the velocity error increases the lag between the set-point and the controlled variable.

Decreasing the controller sensitivity to reduce the overshoot causes the system response to be sluggish and increases the velocity error.

Compensating for the time delay in the controlling device to prevent hunting is done with an anti-hunt device. Anti-hunt devices for damping are many and varied. Some anti-hunt devices are inertia dampers and some involve elaborate and complex electronic systems. A satisfactory anti-hunt device provides negative feedback when the error signal is small, and positive feedback when the error signal is large.

Figure 12-12 represents the response of the system with three different types of damping. Curve A shows a system when it is underdamped, in which case overshoot is pronounced, but the oscillations finally cease. Curve C shows a system that is overdamped. In this case the speed of response of the system is reduced by reducing the gain of the controller. Curve B is a critically damped system. The value of damping applied is the smallest amount necessary to eliminate overshoot. The frequency response of an automatic control system may be obtained by plotting the transfer function of the system using a Bode diagram, or by plotting the results of data obtained experimentally in the laboratory.

The Bode diagram was developed by H.W. Bode. These diagrams are approximate responses using asymptotic straight lines. The diagram is two graphs: one of gain and versus frequency, and one of phase shift versus frequency. The gains are usually plotted in logarithmic or db values.

$$\boxed{\text{db gain} = 20 \log \frac{E_o}{e_{in}}} \qquad (12.23)$$

The frequency is often converted into radians/sec. The Bode diagram is generally plotted on 3- or 4-cycle semilog paper. As an illustration, the Bode diagram of the R-C network shown in figure 12-13 will be constructed. The first step in constructing the Bode diagram is to determine the transfer function. The transfer function of the network is

$$e_o = \frac{e_{in}(-jX_c)}{R - jX_c}$$

$$\frac{e_o}{e_{in}} = \frac{-jX_c}{R - jX_c}$$

$$\frac{e_o}{e_{in}} = \frac{-jX_c}{R - jX_c} \times \frac{\frac{1}{-jX_c}}{\frac{1}{-jX_c}}$$

$$\frac{e_o}{e_{in}} = \frac{1}{\frac{-R}{jX_c} - \frac{jX_c}{-jX_c}} = \frac{1}{\frac{-R}{jX_c} + 1}$$

$$\frac{e_o}{e_{in}} = \frac{1}{1 + jR/X_c} = \frac{1}{1 + j\omega RC}$$

$$\frac{e_o}{e_{in}} = \frac{1}{1 + j\omega(0.01)} = \frac{1}{1 + j\omega/100} \qquad (12.24)$$

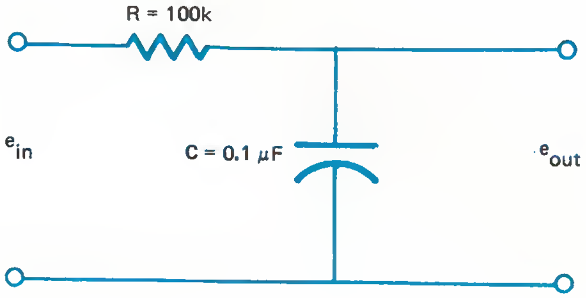


Fig. 12-13 R-C Network

An inspection of the network in figure 12-13 and equation 12.24 reveals that at low values of $\omega (\omega < 100)$ the output voltage will equal the input voltage. At $\omega = 100$, the phase angle is 45° and the output voltage is 0.707 (-3 db) of the input voltage. At larger values of $\omega (\omega > 100)$, the output voltage decreases at a rate of 20 db per frequency decade (10). Therefore, a sketch of the gain versus frequency portion of the Bode diagram for this network can be made with one asymptotic line drawn from $\omega = 1$ radian/sec to the corner frequency, $\omega = 100$ radian/sec, at 0 db gain. Then another asymptotic line is drawn from $\omega = 100$ radians/sec and 0 db gain to 1000 radians/sec (1 decade higher) and -20 db gain. This construction is shown in figure 12-14. The maximum error occurs at the corner frequency where the response is actually -3 db down.

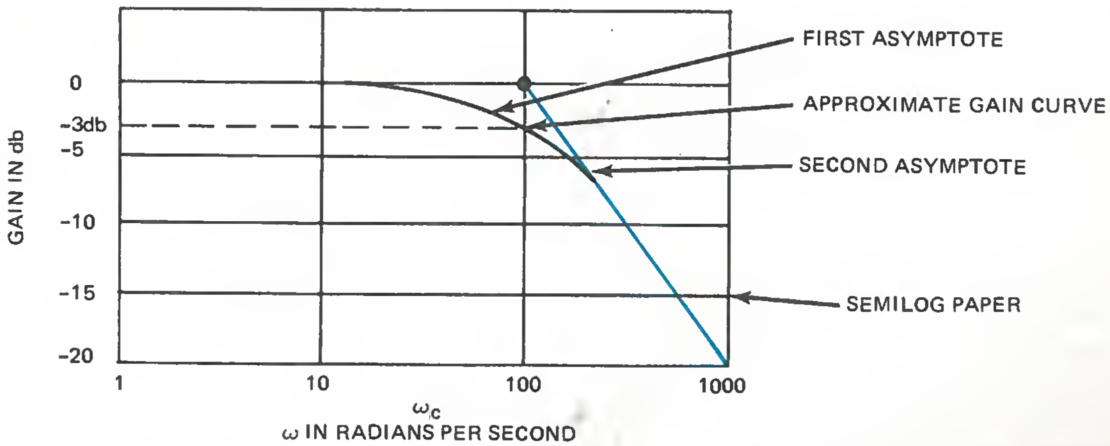


Fig. 12-14 Bode Diagram Showing Gain Versus Frequency

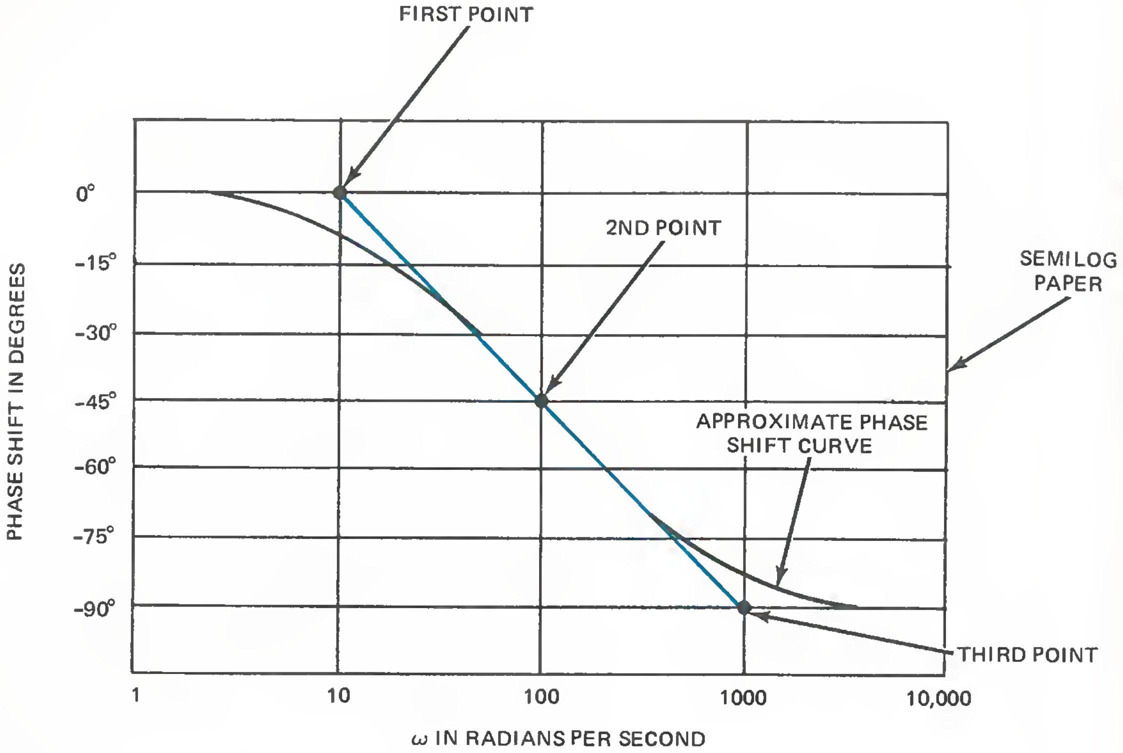


Fig. 12-15 Bode Diagram Showing Phase Shift Versus Frequency

To plot the phase shift of the network, three points are identified. First, mark the point 0° phase shift at 1/10 of the corner frequency. Second, mark the point -45° phase shift at the corner frequency. Third, mark the point -90° at 10 times the corner frequency. This construction is shown in figure 12-15. The maximum error occurs at 1/10 the corner frequency (ω_c) and 10 times the corner frequency. The amount of error is -6° at 1/10 ω_c and +6° at 10 ω_c.

The method of constructing the Bode diagram for a transfer function of an automatic control system is the same; however, the transfer function is much more involved.

To construct the frequency response curve using data obtained in the laboratory, a two-channel oscillograph is used to record input and output voltage waves simultaneously. From these traces, the gain in db and the phase shift in degrees is obtained and recorded. From the data recorded, the frequency response showing gain and phase lead or lag is plotted on semilog paper. A typical oscillograph is shown in figure 12-16. From the oscillograph the following information can be obtained:

1. Frequency

$$F = 1/t$$

$$t = \frac{\text{No. of cm for 1 cycle}}{\text{oscillograph speed}}$$

$$= \frac{4 \text{ cm}}{2 \text{ cm/sec}} = 2 \text{ sec}$$

$$F = \frac{1}{t} = \frac{1}{2 \text{ sec}} = 0.5 \text{ cycles/sec}$$

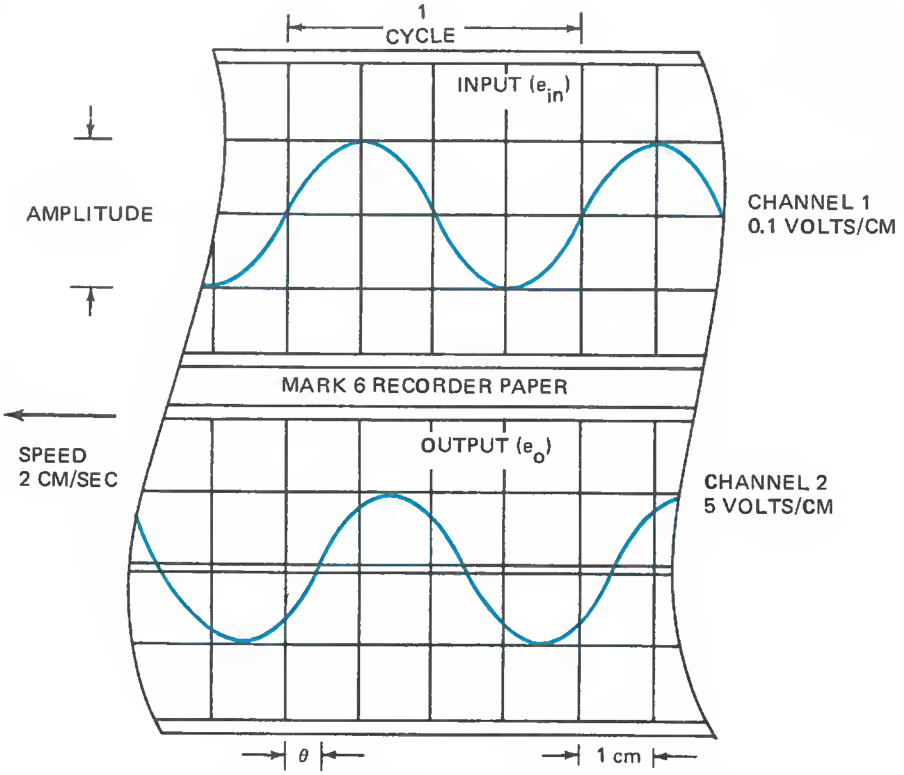


Fig. 12-16 Oscillograph Recording used to Determine Frequency Response

2. **Input voltage (e_i)**

   e_i = (No. of cm for peak-to-peak in input)(voltage/cm setting)

   e_i = 2 cm (0.1 volts/cm) = 0.2 volts

3. **Output voltage (e_o)**

   e_o = (No. of cm for peak-to-peak output)(voltage/cm setting)

   e_o = 2 cm (5 volts/cm) = 10 volts

4. **Gain (A_v)**

   $$A_v = \frac{e_o}{e_{in}} = \frac{10}{0.2} = 50$$

5. **Gain (db)**

   $$A_{db} = 20 \log \frac{e_o}{e_{in}}$$

   $$A_{db} = 20 \log \frac{10}{0.2} = 20 \log 50$$

   $$A_{db} = 20(1.7) = 34.0 \text{ db}$$

6. **Phase shift**

   θ = (No. of cm of shift)(No. of degrees/cm)

   θ = 1/2 cm (90°/cm) = 45°

It should be pointed out that the elements of an analog computer are so similar in their action to elements of a control system that they are frequently used in the design and analysis of automatic control systems.

MATERIALS

1 Transistor, 2N1304 or equivalent
3 Resistor, 1 kΩ 1/2W
1 Resistor, 100Ω 1/2W
1 Resistor, 68 kΩ 1/2W
1 Resistor, 12 kΩ 1/2W
1 Potentiometer, 0-20k 1/2 watt (10 turns)
2 Capacitor, 100 μF, 15 VDC
1 Capacitor 10 μF, 15 VDC
1 DC Power supply, 0-40V at 30 mA
2 Strip chart recorder, 0-10 cm/sec
1 Generator, function 1 Hertz to 100 Hertz
1 Oscilloscope

PROCEDURE

1. Construct the experimental circuit shown in figure 12-17.

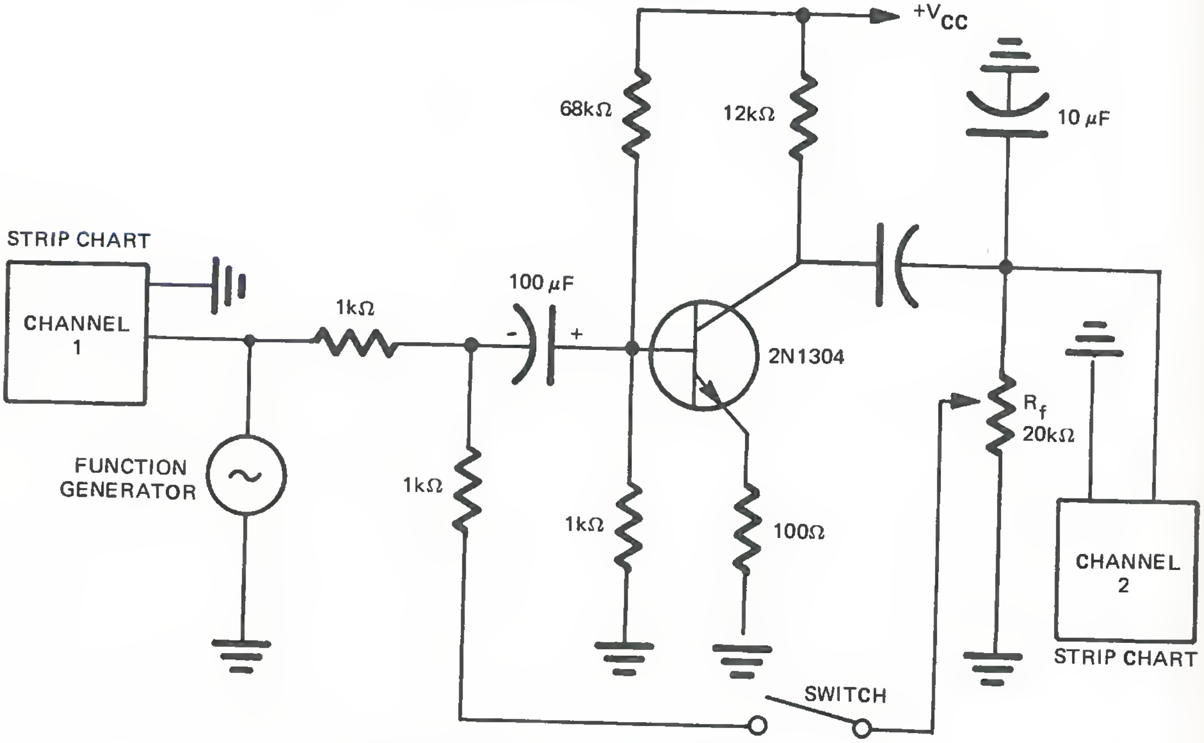


Fig. 12-17 Experimental Test Circuit

2. With S_1 open and the frequency of the audio oscillator set at 1 Hertz, adjust the output of the oscillator to 0.5 volts peak-to-peak.

3. Set the channel 1 sensitivity (volts/cm) of the strip chart recorder to a convenient position (peak-to-peak swing of about 2 cm). Leave the chart drive motor off.

4. Record the value in figure 12-18 as V_1/cm.

5. Set the channel 2 sensitivity (volts/cm) of the strip chart recorder to a convenient position (peak-to-peak swing of about 2 cm).

6. Record this value in figure 12-18 as V_2/cm.

Freq.	V_1/cm	V_1	V_2/cm	V_2	A_v	θ
1 Hertz						
3 Hertz						
5 Hertz						
10 Hertz						
15 Hertz						
25 Hertz						
40 Hertz						
60 Hertz						

Fig. 12-18 Open Loop Data Table

7. Set the strip chart recorder speed to 10 cm (or maximum) per second. **Do not engage chart drive motor.**
8. Record the speed in figure 12-18 as cm/sec.
9. Engage the chart motor and obtain 3 or 4 cycles of signal voltage. **Note: Do not take a longer time than really necessary.**
10. From the chart trace, calculate V_1 using

$$N_1 = (\text{No. of cm of swing}) \times V_1/\text{cm}$$

11. Record it in the Data Table as V_1.
12. From the chart trace, calculate V_2 using

$$V_2 = (\text{No. of cm of swing}) \times V_2/\text{cm}$$

13. Record it in the Data Table as V_2.
14. Calculate the gain using

$$A_v = \frac{V_2}{V_1}$$

15. Record the result in the Data Table as A_v.
16. From the chart trace, determine the number of degrees per cm, using successive positive peaks.
17. Determine the number of cm of lead or lag of V_2 with respect to V_1 using the zero voltage cross-over point.

18. Calculate the phase angle using

$$\theta = (\text{No. of degrees/cm})(\text{No. cm of lead or lag})$$

19. Record this value in the Data Table as θ. **Note: If V_2 lags V_1, θ is negative. If V_1 lags V_2, θ is positive.**

20. Repeat steps 2 through 19 for 3 Hertz, 5 Hertz, 10 Hertz, 15 Hertz, 25 Hertz, 40 Hertz and 60 Hertz.

21. With S_1 closed and the frequency of the oscillator at 1 Hertz, adjust R_f until the output voltage, V_2, is one-fourth the value recorded in step 12 for 1 Hertz. The input voltage V_1 remains at 0.5 volts.

22. Repeat steps 3 through 20 and record the results in figure 12-19.

Freq.	V_1/cm	V_1	V_2/cm	V_2	A_v	θ
1 Hertz						
3 Hertz						
5 Hertz						
10 Hertz						
15 Hertz						
25 Hertz						
40 Hertz						
60 Hertz						

Fig. 12-19 Closed Loop Data Table

ANALYSIS GUIDE. Plot a Bode diagram for the experimental results. Using both open loop and closed loop data on the same graph, plot (1) gain versus frequency (in radians per sec) and (2) phase angle versus frequency. In a written analysis, compare the frequency response of the open loop and closed loop systems.

PROBLEMS

1. Draw the block diagram of the system shown in figure 12-17.

2. A test of a pneumatic transducer in the laboratory provides the following information:

psi In	E Out
5	1 volt
7.5	1.5 volts
10	1.75 volts

Calculate the gain of the transducer and determine the range of linear operation.

3. Discuss the dead band of a process control.

4. Calculate the transfer function and sketch the Bode diagram of the electrical circuit shown in figure 12-20.

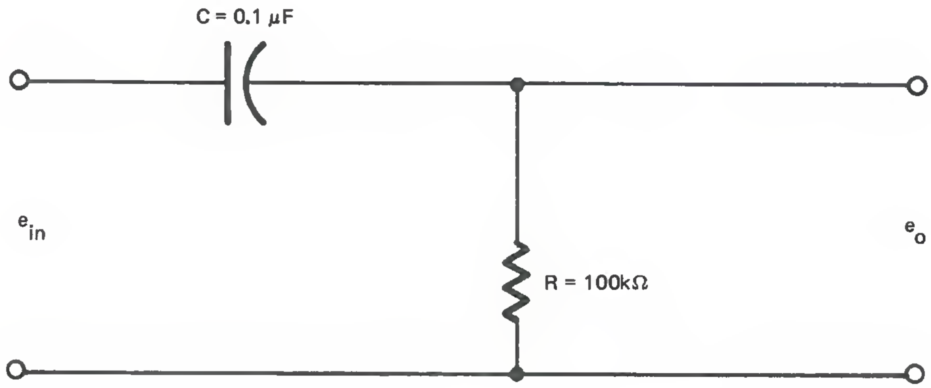


Fig. 12-20 Circuit for Problem 4

experiment 13 *POSITION CONTROL SYSTEMS*

INTRODUCTION. A servomechanism is an automatic control system in which the controlled is a mechanical position or rotation. In this experiment a servomechanism will be examined.

DISCUSSION. Servomechanisms have been used to aim large guns, control the rudders of ships, guide missiles and space vehicles, to control milling machines, and to control the position of a pen of a plotter instrument.

An example of a servomechanism is shown in figure 13-1. The objective of the system is to produce an angular position of the load that is in exact correspondence with the angular position of the input shaft.

Assume that the output angular position, θ_o, is in exact correspondence with the input angular position, θ_i. The feedback voltage, f, is equal to the control voltage, c, and the error voltage, e, (the deviation) is zero. Therefore, the output of the amplifier is zero and the DC motor is at a standstill. The control potentiometer could be a gyro (device that senses position and/or rate) or a set-point reference. The follow-up potentiometer may be classified as a transducer, since it converts mechanical position to an electrical signal. The DC motor could be a hydraulic or pneumatic actuator.

If the wiper of the control potentiometer suddenly moves up to a new position simulating a step input in θ_i, the voltage c will be greater than voltage f and an error voltage + e will be generated. The error voltage is amplified and fed to the motor. The motor shaft will rotate until the new angular position of θ_o is in exact correspondence with θ_i. At this new position, voltage c will be equal to voltage f and the error voltage is reduced to zero. With insufficient damping, the motor shaft would overshoot and generate an error signal of the opposite polarity. This would cause the motor shaft to reverse direction. This time the shaft may undershoot the desired value but by a smaller amount and the process is repeated. This hunting (oscillation) is caused by the in-

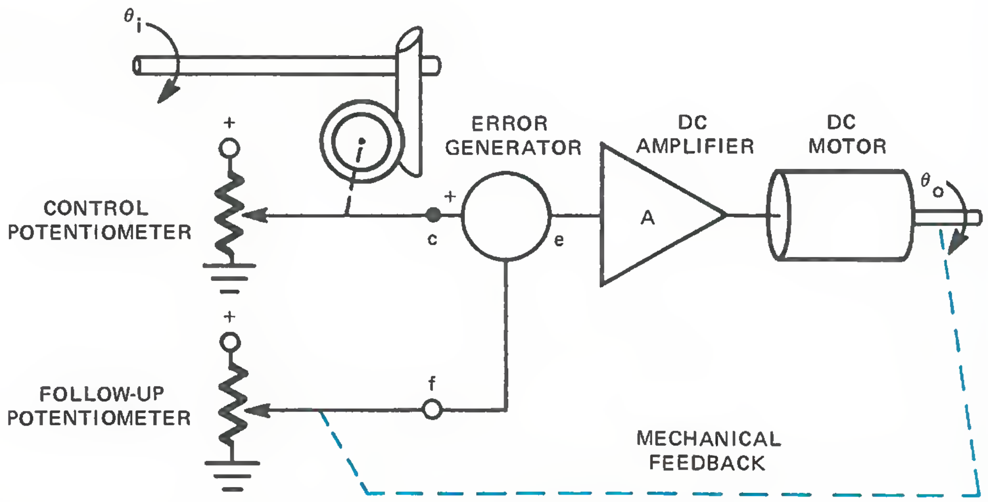


Fig. 13-1 Simple Servomechanism

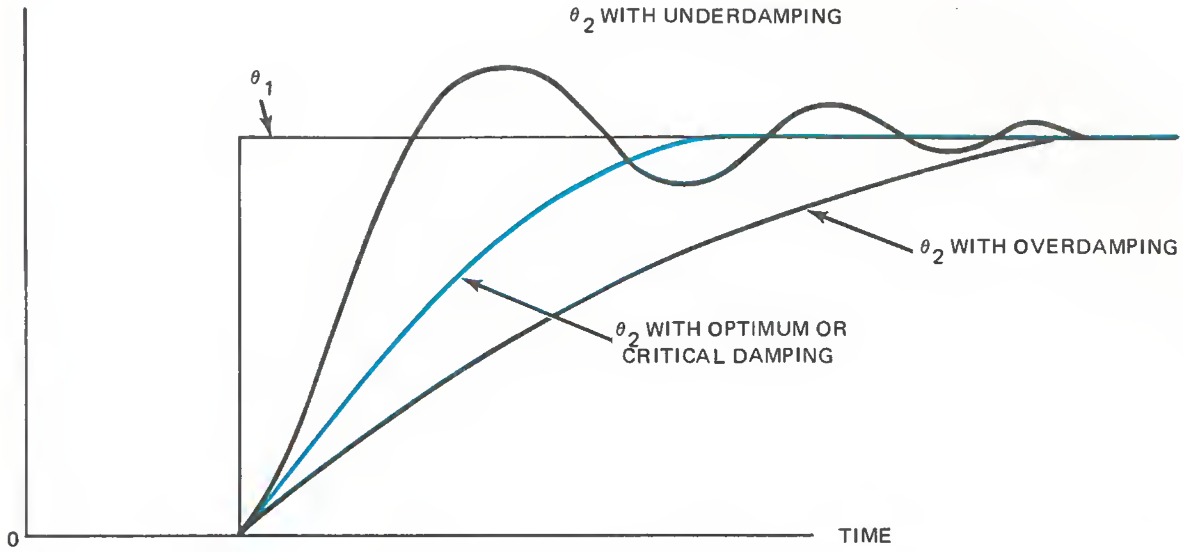


Fig. 13-2 Damping Effects on Output

ertia of the rotating mass, but due to frictional resistance, the oscillations will die away. The rapidity with which the oscillations cease to exist is a measure of the damping required for critical damping. As the amplifier gain is increased, so is the tendency to overshoot, and a greater amount of damping is required for satisfactory transient response. The transient response of an automatic control system is usually tested using a step function input.

Viscous friction may be introduced in samll servo systems to reduce oscillations. Viscous damping increases the energy losses in the system and also increases the time required for the output shaft to move to the new position.

Damping may be achieved without a great expenditure of energy by the addition of a tachgenerator, or by an electrical network placed in the feedback path of the amplifier itself. The network shown in figure 13–3 provides an output voltage that is proportional to the input voltage plus its rate of change. The network is sometimes called a phase advance network. A system using this type of control action is termed a proportional plus derivative system.

The network shown in figure 13–3 is satisfactory for low-power systems in which the load on the motor is small and constant. But for varying actuator loads, misalignment

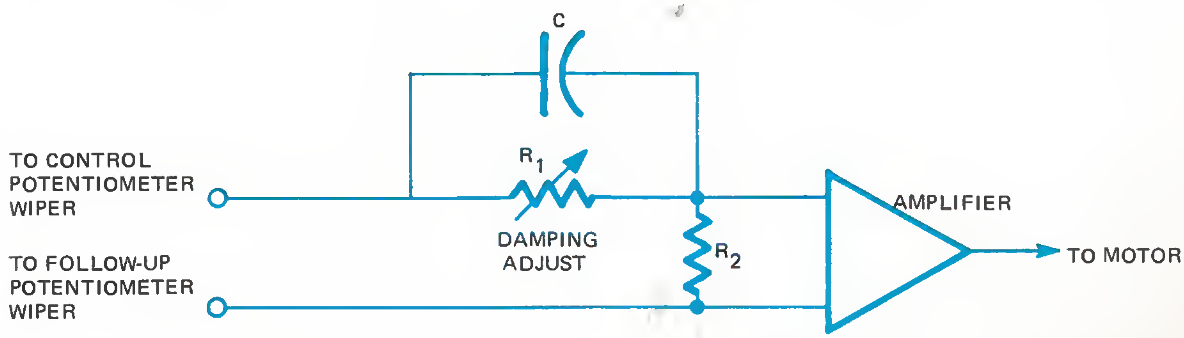


Fig. 13-3 Proportional Plus Derivative (rate) Network

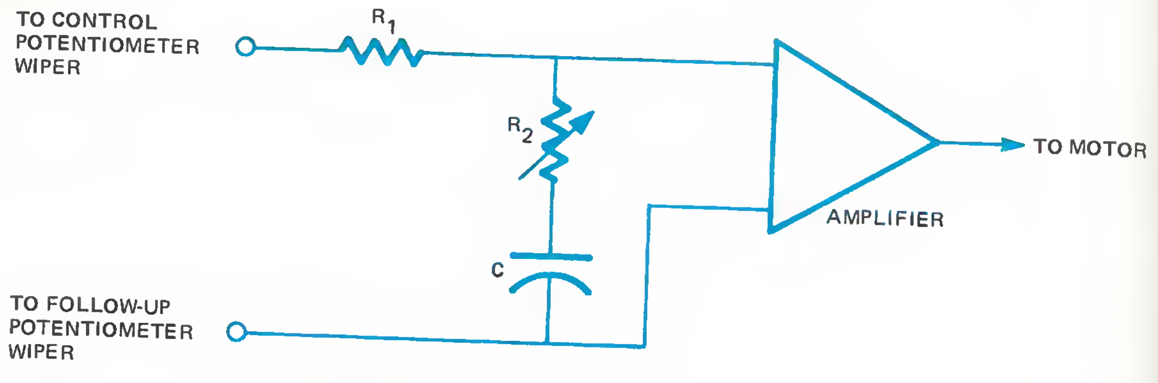
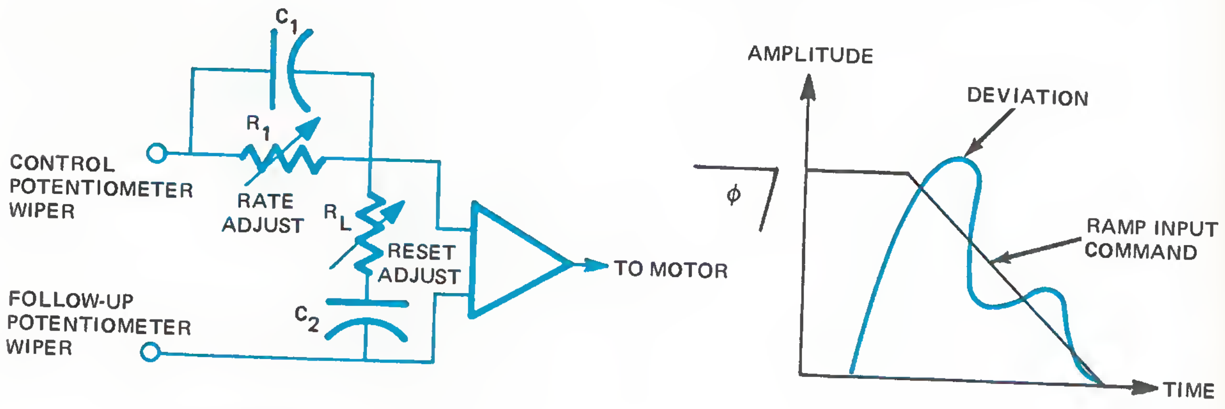


Fig. 13-4 Proportional Plus Integral (reset) Network

will increase as the power required increases. This steady-state error may be eliminated by adding integral control action. The network shown in figure 13–4 provides an output that is proportional to the time integral of the deviation. As long as there is a deviation between the desired value and the actual controlled variable, the amplifier output will continue to increase until the deviation is reduced to zero. The optimum network would provide an output that is proportional to the deviation, an output that is proportional to the rate of change of deviation, and an output that is proportional to the time integral of the deviation. Such a network is shown in figure 13–5 and the response curve of the error signal to a ramp function is also shown.

Besides the inertia of the moving masses, there are time delays due to inductance, backlash in gear trains, resilence of shafts, etc. that cause the output to lag behind the input. All of these factors tend to reduce the stability of the control system. Should the output delay the input by 180 degrees, the error voltage generated will be increased instead of decreased. If the increase in output for a given deviation is greater than the original change of deviation, the system will become self-oscillatory.

Nyquist showed that, for systems which are stable under open-loop conditions, if the locus of the tip of the response vector passes through or encloses the point $-1 + j0$, the sys-



(A) NETWORK

(B) RESPONSE TO RAMP

Fig. 13-5 Proportional-Plus-Reset-Plus-Rate

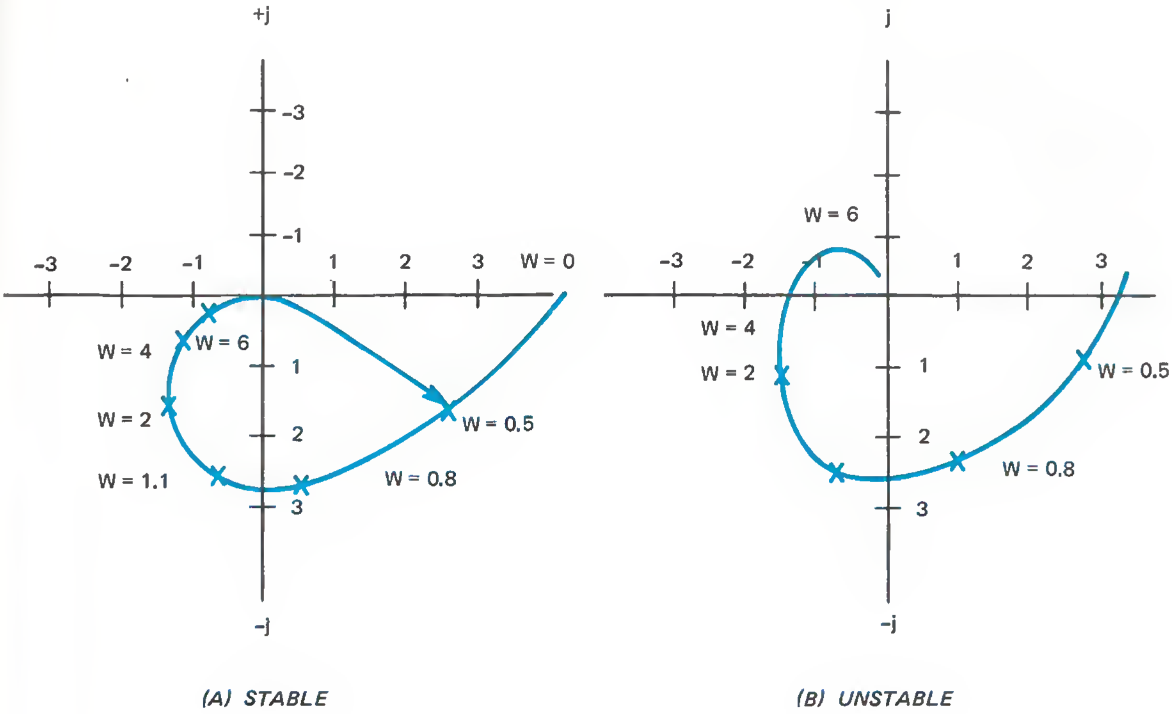


Fig. 13-6 Nyquist Diagrams

tem will be unstable when the loop is closed. If the locus does not pass through or enclose this point, the system will be stable when the loop is closed. A harmonic response locus or Nyquist diagram is shown in figure 13-6.

The response vector may be obtained with the circuit shown in figure 13-1. The feedback loop is opened and a sinusoidal voltage of constant magnitude e is applied to the input of the error generator. The control voltage input c to the error generator is zero. Providing the system is linear, the output V_o will be a sinusoidal voltage with a magnitude and a phase depending on the elements of the system. The ratio of V_o/e is the length of the response vector, and the phase difference may be measured with an oscillograph or oscilloscope. The response of the amplifier is recorded as

$$\frac{V_o}{e} \angle\theta \qquad (13.1)$$

This value in equation 13-1 is converted to the form

$$\frac{V_o}{e}\cos\theta \pm j\,\frac{V_o}{e}\sin\theta \qquad (13.2)$$

Data is obtained for various frequencies, and these values are plotted on a rectangular coordinate graph. Hence, the Nyquist diagram is obtained from frequency response analysis.

It should be emphasized that the testing of a servomechanism usually involves measuring the response of the system to various types of input signals. The most commonly used inputs are:

A) The step or square wave for transient response testing

B) The sine wave for frequency response testing

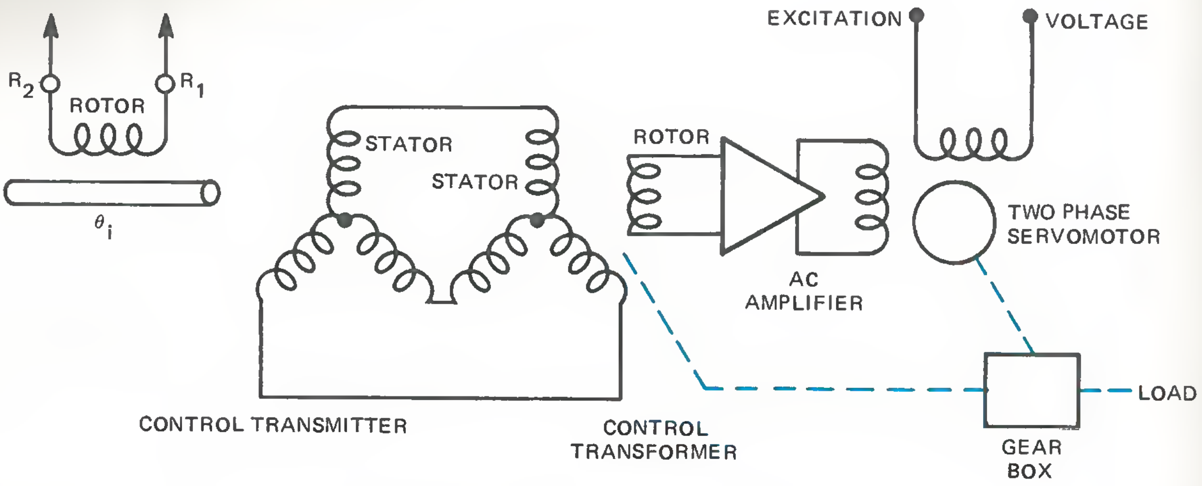


Fig. 13-7 AC Position Control System

A simple AC position control system is shown in figure 13–7. The system uses a control transmitter and a control transformer to convert the mechanical angular position to an electrical error signal. The error signal is amplified by an AC amplifier which drives a two-phase servomotor. The output of the servomotor is mechanically connected to the load and the rotor of the control transformer through a gear mechanism. A high power-to-weight ratio is obtained from a servomotor running at high speed, and therefore, a gear device becomes necessary when the speed of the final drive shaft is lower than that for which the servomotor can conveniently be designed. The gear box adds friction, resilence and inertia to the system, but the most serious problem is that of backlash.

MATERIALS

1 Function generator, sine and square wave
2 Strip chart recorder
2 Potentiometers, 10 kilohm, 4 watt, continuous rotation
1 Amplifier, DC with variable gain and damping
1 Permanent magnet, DC gearhead motor
1 DC power supply, 0–40V
1 Capacitor, 100 μF

PROCEDURE

1. Connect the experiment circuit shown in figure 13–8.
2. With the damping adjustment set to zero and the sensitivity (gain) set to minimum, manually rotate the shaft of the control potentiometer until the voltage from the wiper to common is 3 volts DC.
3. With a differential voltmeter connected from the wiper of the control potentiometer to common, very carefully rotate the control potentiometer shaft clockwise until the servomotor just responds.
4. Record the differential voltmeter reading.

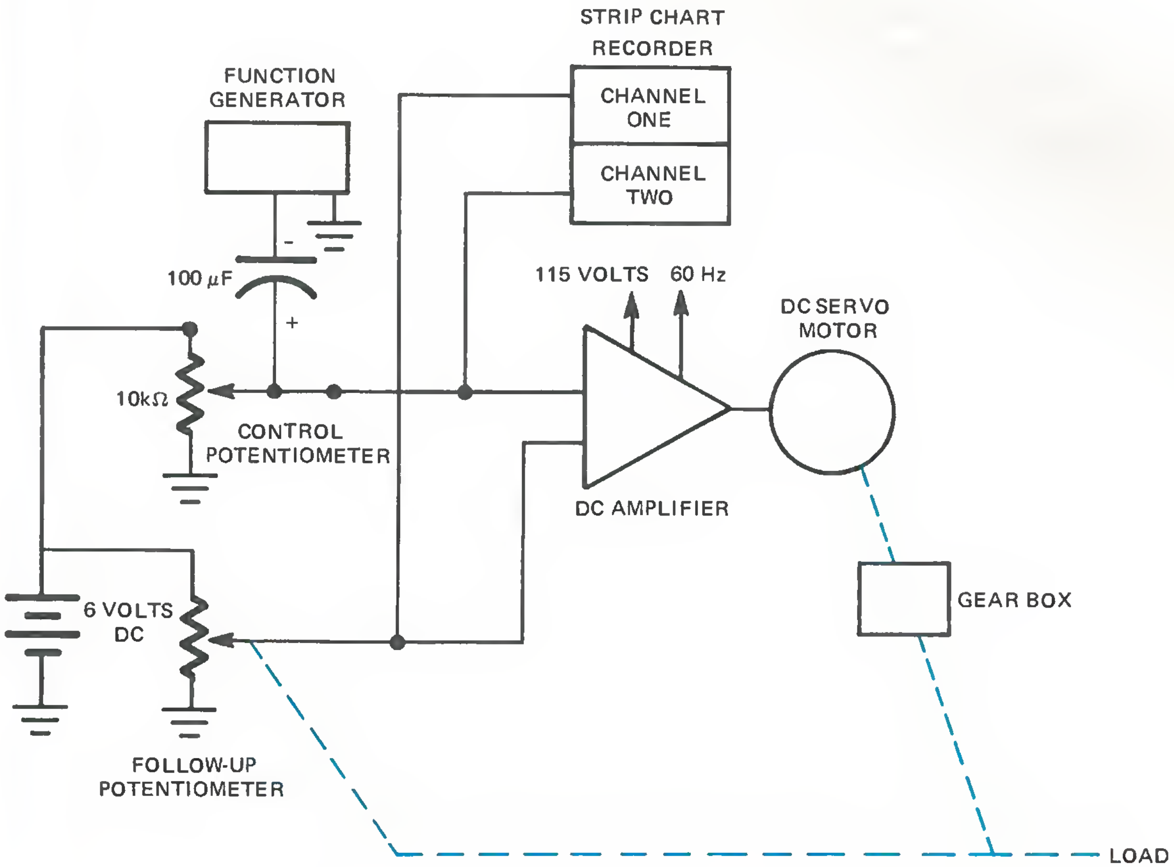


Fig. 13-8 The Experimental Circuit

5. Very carefully rotate the control potentiometer shaft counterclockwise until the servo motor just responds.
6. Record the differential voltmeter reading.
7. Determine the dead band by subtracting the voltage measured in step 4 from the voltage measured in step 6.
8. Repeat steps 2 through 7 with the sensitivity adjustment set at 1/2 and the maximum position.
9. Set the sensitivity to the minimum and the damping adjustment to zero.
10. With the strip chart recorder on, quickly rotate the control potentiometer (CW or CCW) out of the dead band. This simulates a step input.
11. From the strip-chart recorder trace of the follow-up potentiometer wiper, determine the number of overshoots of the motor.
12. Repeat steps 9 through 11 for the damping adjustment at 1/4, 1/2, 3/4 and at maximum.
13. Repeat steps 9 through 12 with the sensitivity setting at 1/2 and the maximum position.

14. Set the frequency of the function generator for a 0.1 Hertz sine wave and set its amplitude to a value sufficient to cause the servomotor to rotate in one direction, then in the other.

15. Set the damping adjustment to approximate critical damping (no overshoots) with the sensitivity setting at approximately a minimum.

16. Switch the strip chart recorder on and obtain 2 or 3 cycles of the motion of the motor. Label the strip chart record with sufficient information to identify the test conditions.

17. Repeat steps 14 through 16 for 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 4.0 and 6.0 Hertz.

18. Repeat steps 14 through 17 for a sensitivity setting at 1/2 the maximum position.

19. Prepare a neat Data Table and enter all your data in it.

ANALYSIS GUIDE. Discuss the effect of increasing or decreasing the sensitivity on the dead band. Discuss the effect of the damping control on oscillation or hunting. Discuss overdamped, underdamped and critical damped system control. Plot graphs of gain and phase shift versus the frequency (Bode plots).

PROBLEMS

1. Discuss the advantages of critical damping over underdamping and overdamping.
2. A DC servomechanism is to be tested for its steady-state frequency response. Draw the schematic of the test circuit showing all instruments and connections.
3. Repeat problem 2 for an AC servomechanism.
4. Construct a simplified Nyquist diagram for the circuit shown in figure 13-9.

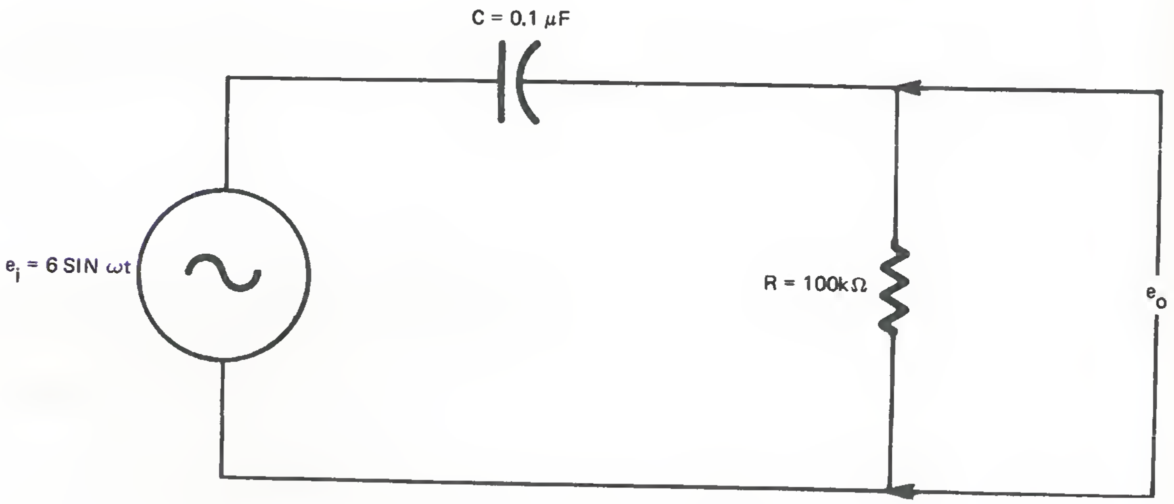


Fig. 13-9 Circuit For Problem 4

ω	e_i	e_o	$\frac{e_o}{e_i}$	θ	$\frac{e_o}{e_i} \sin\theta \pm \frac{e_o}{e_i} \cos\theta$
0					

Data for Problem 4

experiment 14 VELOCITY CONTROL SYSTEMS

INTRODUCTION. Many times in industry it is necessary to control the speed of a rotating shaft. Frequently, manual control is inadequate: therefore, automatic control is essential. Hydraulic and pneumatic motors are often used, but the vast majority are electric. In this experiment, some velocity control systems will be examined.

DISCUSSION. With slight modification, the servomechanism position control system can be used to control the speed of an output shaft. Such systems, known as rate or velocity systems, generally employ a tach generator. The tach generator produces a voltage that is proportional to its speed. This output voltage is applied to an error generator. The error generator compares the tach generator output with the reference input voltage. If there is a difference between the two voltages, an error signal results. The error signal is amplified to correct the speed of the motor. The speed of the output shaft is determined by the magnitude of the reference input and the feedback voltage from the tach generator. For each value of reference input, there is a corresponding value of motor speed. Speed variations under conditions of varying loads may be considerably reduced by this type of the feedback.

A simple system for the control of a two-phase motor is shown in figure 14–1. To solve for the system equation relating the speed of the output shaft to the command voltage, start with the actuator equation and proceed as follows:

$$S_1 = K_aE$$

But

$$E = K_ce$$

Therefore

$$S_1 = K_a\,(-K_ce)$$

But

$$e = C - f$$

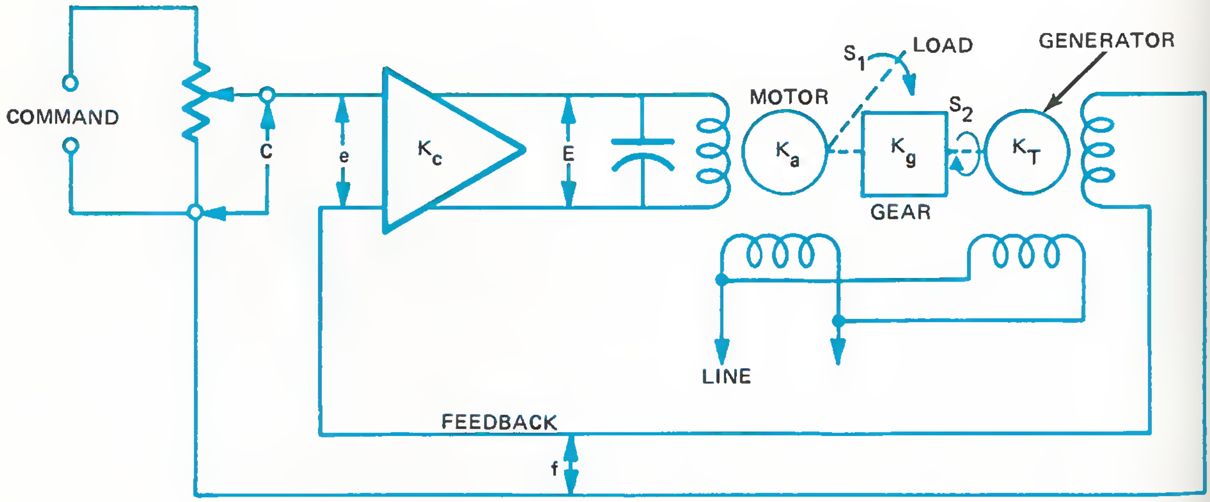


Fig. 14-1 Automatic Speed Control

Therefore

$$S_1 = -K_aK_c\,(C - f)$$

But

$$f = K_TS_2$$

Therefore

$$S_1 = -\,K_aK_c\,(C - K_TS_2)$$

But

$$S_2 = K_gS_1$$

Therefore

$$S_1 = -\,K_aK_c\,(C - K_TK_gS_1)$$

Expanding,

$$S_1 = -\,K_aK_cC + K_aK_cK_TK_gS_1$$

$$S_1 - K_aK_cK_TK_gS_1 = -\,K_aK_cC$$

$$S_1 = \frac{-K_aK_c}{1 - K_aK_cK_TK_g}\;C \qquad \textbf{(14.1)}$$

Examining equation 14.1 and the system diagram in figure 14-1, it can be seen that K_aK_c is the open loop gain of the system and K_TK_g is the feedback constant. Thus the performance of speed control systems can be represented by the same equations derived for an amplifier with feedback. In practice, $K_aK_cK_TK_g$ will be much greater than one, so that the motor speed will depend only on the command setting voltage C and the gain of the controller and actuator. The output speed of the system can be virtually independent of load changes and line voltages.

The accuracy of a speed control system may be defined as the deviation from the desired speed caused by the application of full-load torque. This accuracy is expressed as a percentage of the maximum speed. The control gain of the system is defined as the tachometer output per volt of amplifier input when the feedback path is open.

$$G = \frac{f}{e} = \frac{K_TK_gS_1}{e} \qquad \textbf{(14.2)}$$

When the loop is closed,

$$e = C - K_TK_gS_1$$

Then

$$G = \frac{K_TK_gS_1}{C - K_TK_gS_1}$$

$$K_TK_gS_1 = \frac{G}{1 + G}\;C \qquad \textbf{(14.3)}$$

Thus, the greater the control gain, the closer will $K_TK_gS_1$ be to C. For high accuracy, a high gain is required.

Control systems that must deliver several hundred horsepower are sometimes controlled by the Ward-Leonard system shown in figure 14-2. This system makes use of the amplifying properties of the separately-excited DC generator. The DC generator supplies a controllable voltage to the armature of a DC motor. The generator is usually driven by an AC induction motor. The speed of the motor is controlled by adjusting the generator field current, which, in turn, varies the armature voltage supplied to the motor, or by adjusting the motor field current. In general, the DC field is produced by a small DC generator called an exciter. The exciter is mounted on the shaft of the motor-generator set. Although

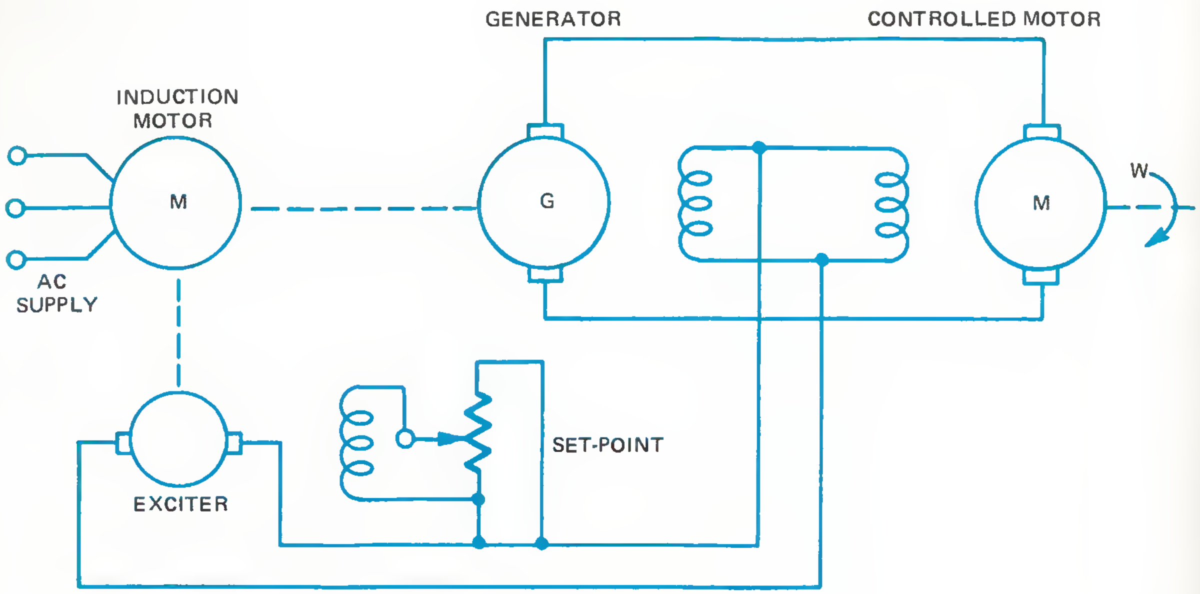


Fig. 14-2 Ward-Leonard Speed Control

such a system requires a large initial investment, it is particularly useful when large quantities of power must be controlled over an extensive speed range. The control elements are located in the low-power circuits.

Figure 14-3 shows a Ward-Leonard system used for closed loop control. When the motor shaft speed is at the desired value, the deviation between the tach generator feedback voltage and the command input is zero. Should the load on the motor suddenly increase, decreasing the motor speed, the output of the tach generator is decreased. The deviation between tach generator output and the command input causes an error signal to be genera-

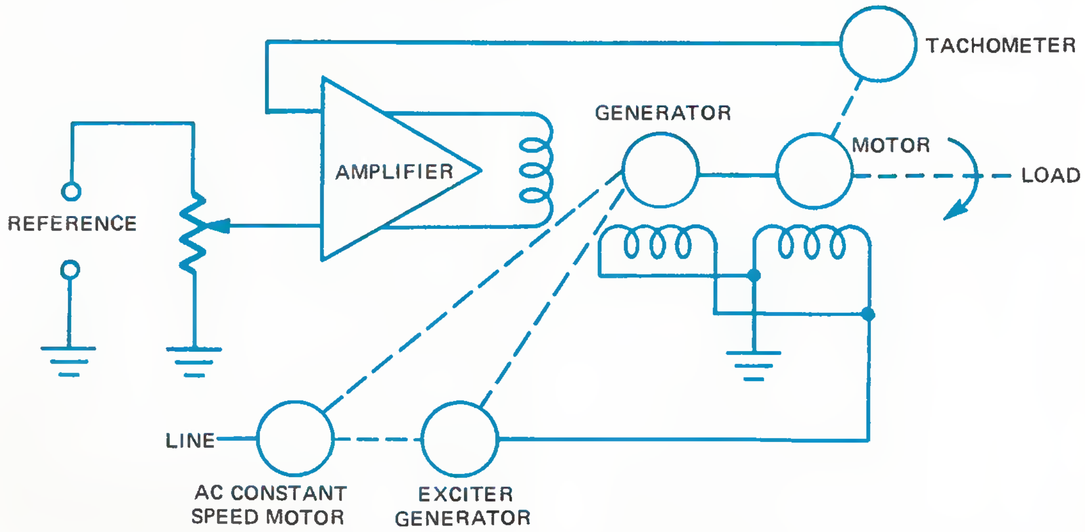


Fig. 14-3 Ward-Leonard System for Closed Loop Control

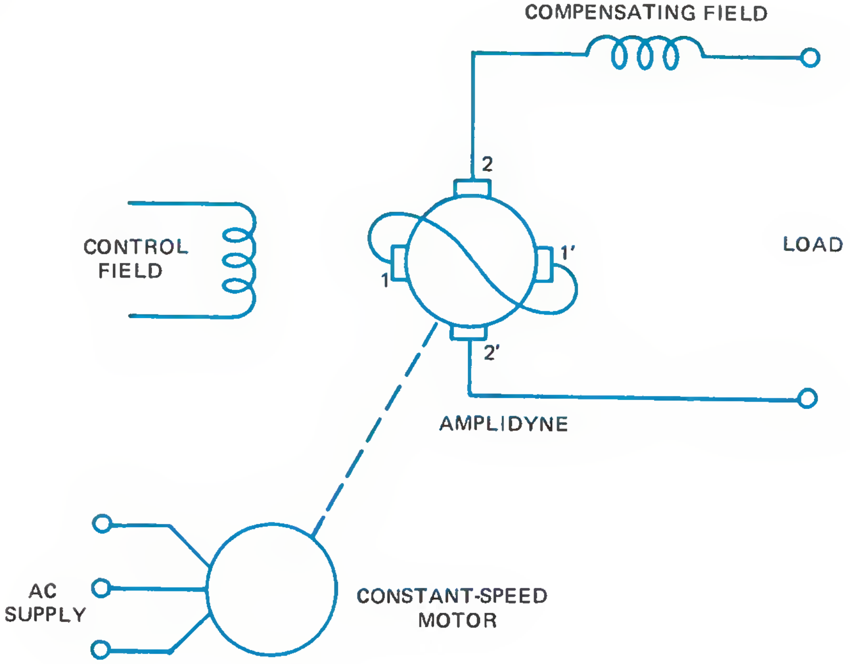


Fig. 14-4 The Amplidyne

ted. This error signal causes the field current of the DC separately-excited generator to increase. This increase in field current produces more flux that increases the output voltage of the generator. Since the generator output is the armature supply voltage for the motor, the armature voltage of the motor is increased, increasing the speed of the motor. The motor speed will continue to increase until the deviation between the tach generator output and the command reference is again balanced. A sudden decrease in torque load on the motor causes the motor speed to increase. This causes the tach generator output to increase, and an error signal of the opposite polarity is generated. This error signal decreases the field current of the generator. With decreased field current, the voltage generated by the generator is decreased, decreasing the armature voltage of the motor. The motor's speed will decrease until the deviation between the tach generator output and the reference is again balanced.

The amplidyne is a two-stage rotary amplifier combined in a single machine using one armature. The basic amplidyne is shown in figure 14-4. A DC voltage to the control field establishes a flux through which the armature rotates. The armature of the amplidyne is driven by a constant-speed induction motor. The voltage generated due to the control field current appears between brushes 1 and 1′. This voltage is the output of the first stage. But, brushes 1 and 1′ are shorted together. This short circuit causes a relatively large current to flow. The large current establishes an intense magnetic field. This field induces a voltage into the rotating armature. The voltage between 2 and 2′ is the output of the second stage. When an external load is connected across the output of the amplidyne, the load current flows through the armature winding. The magnetic field produced by the load current partially cancels the input control field. To compensate for this cancellation effect, a compensating winding is added and connected

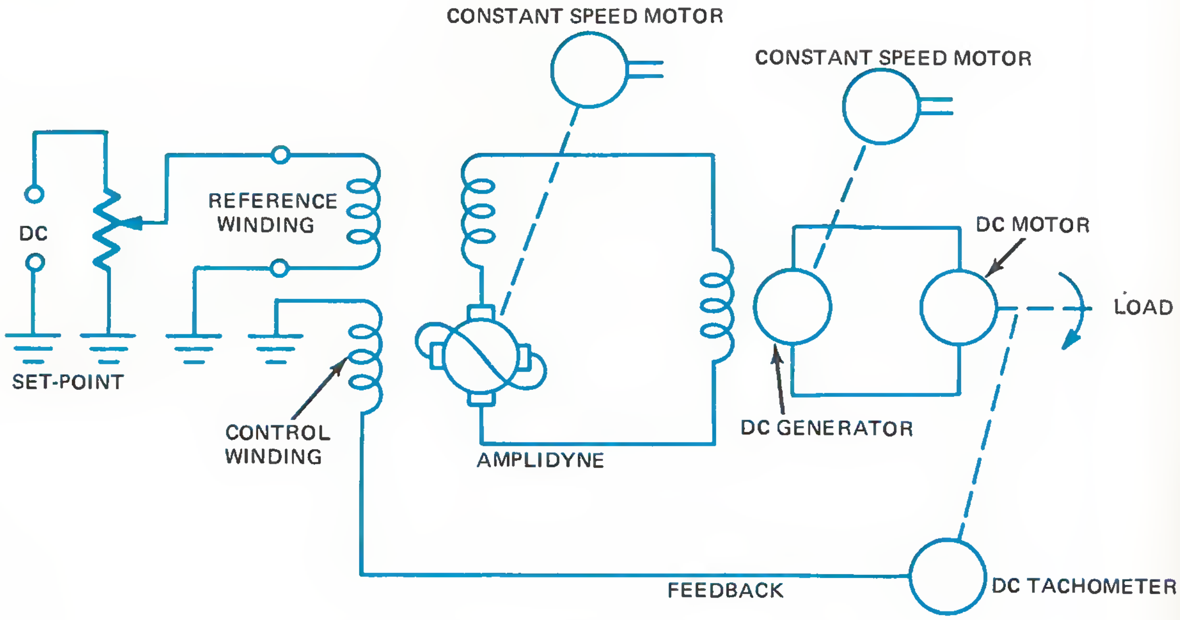


Fig. 14-5 Amplidyne Speed Control System

in series with the load. An increase in load current will increase the strength of the compensating field. The increase in compensating field aids the control field. A small increase in the control input will produce a much greater change in load current. Power gains up to 10,000 are typical of an amplidyne generator.

Figure 14-5 shows a speed control system using an amplidyne generator. The reference field establishes the output level of the amplidyne, while the control field serves as a feedback winding. The control field and the reference field have opposing polarities.

If the torque load on the DC motor increases, the motor speed will decrease and the tach generator output voltage will decrease. The current through the control field decreases. Since the control field opposes the reference field, the net input to the amplidyne is now more than it was. With more input, the amplidyne supplies more output to the field winding of the separately-excited generator. Therefore, the output of the generator increases, increasing the excitation to the armature of the DC motor. As a result, the motor speed increases to its original value.

Another type of amplifier that is used in control circuits is the magnetic amplifier. The magnetic amplifier is shown in figure 14-6. The core material is of the rectangular-loop variety in which the flux density changes abruptly when current reaches a critical value. This characteristic is comparable to that of a silicon-controlled rectifier. The value of the current through the control winding determines the time at which the core will saturate (fire) during the supply voltage cycle.

In figure 14-6, diode D_1 conducts on one half-cycle and diode D_2 conducts on the other half-cycle. During the half-cycle when the current is cut off, the control current resets the flux in that part of the circuit to a value predetermined by the amount of control cur-

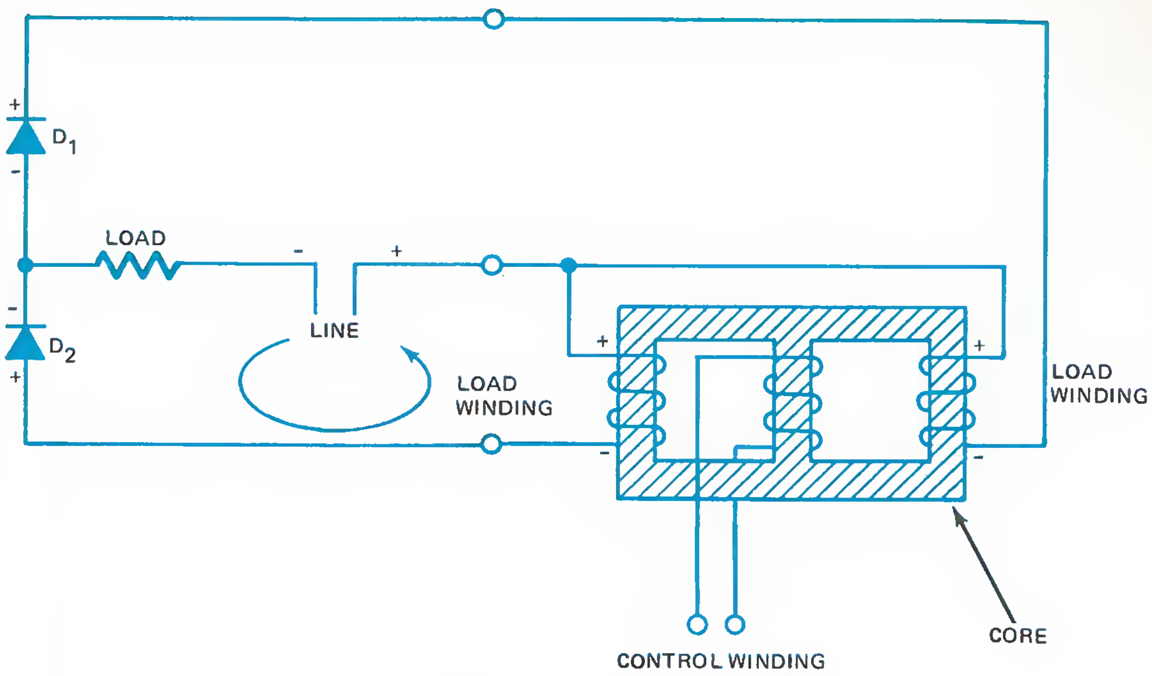


Fig. 14-6 Magnetic Amplifier

rent and the number of turns on the control coil. With this value of flux as the initial point, the load current during the following half-cycle drives the core to complete saturation. The point at which saturation occurs, therefore, depends upon the value to which the flux was previously reset by the control current. If the control current is large, the core remains at complete saturation during the nonconducting half-cycle in the load circuit. Since the core is already saturated, the full half-cycle of supply appears across the load. If the control current is decreased in value, the core will reset to a lower level of flux during the nonconducting half-cycle. The conducting half-cycle must then drive the core from partial to complete saturation before the supply voltage will appear across the load. Still smaller values of control current will reset the flux to lesser values and will require more time lapse before the core saturates. Therefore, a small control current may be used to control large load currents. The control current fires or saturates the core and, therefore, reduces the inductive reactance in series with the load.

A third coil, known as a bias winding, is generally used to reset the value of the flux in the core to negative saturation (opposite direction from that in which the load current saturates the core). The combination of the bias current and control current can, therefore, cause resetting to any value of flux between the limits of negative and positive saturation.

A feedback winding may be included on the magnetic amplifier (saturable reactor). The winding is connected so that current through it produces a magnetic field that either aids or opposes the effect of the control current. If the field aids, it is a positive or regenerative feedback, and a small input will produce an extremely large increase in load current. If the connection is reversed, the feedback will be negative or degenerative. A magnetic am-

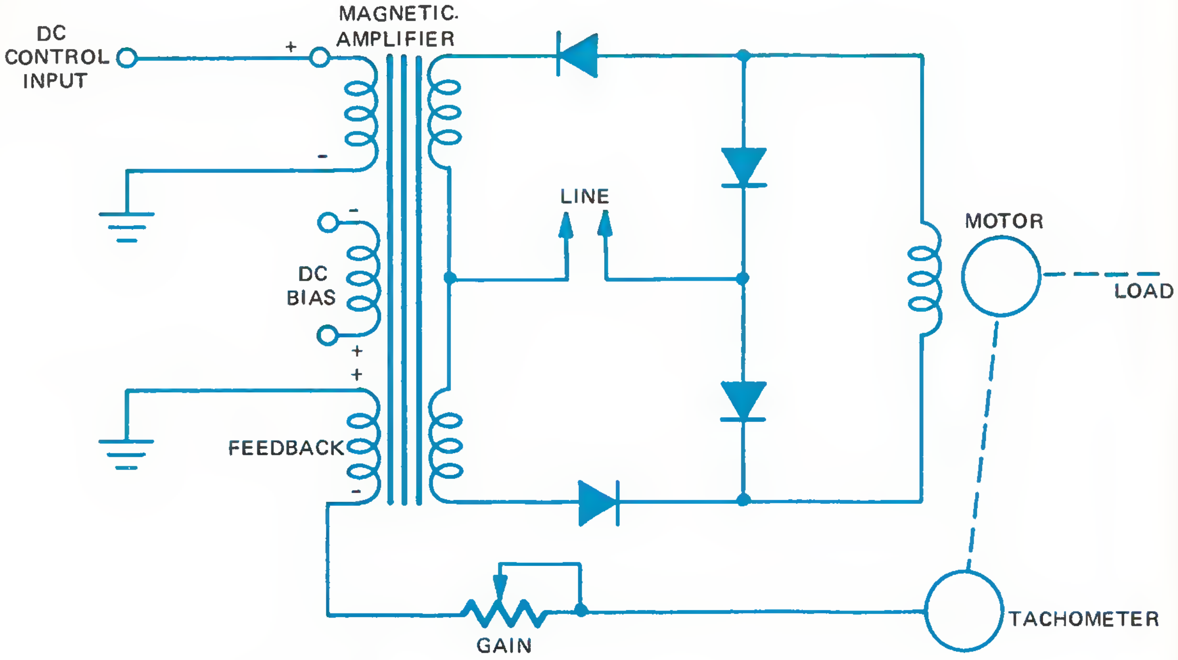


Fig. 14-7 Magnetic Amplifier Speed Control System

plifier using negative feedback to control the speed of a motor is shown in figure 14-7.

Another use of velocity feedback is to provide damping in servomechanisms. The damping is achieved with little expenditure of energy. The system is shown in figure 14-8.

When the controlled variable is in motion, a voltage proportional to its volocity is fed back and subtracted from the voltage obtained between the sliders of the two potentiometers. The method used in the tachogenerator to prevent overshoot and the probability of oscillations is shown graphically in figure 14-9.

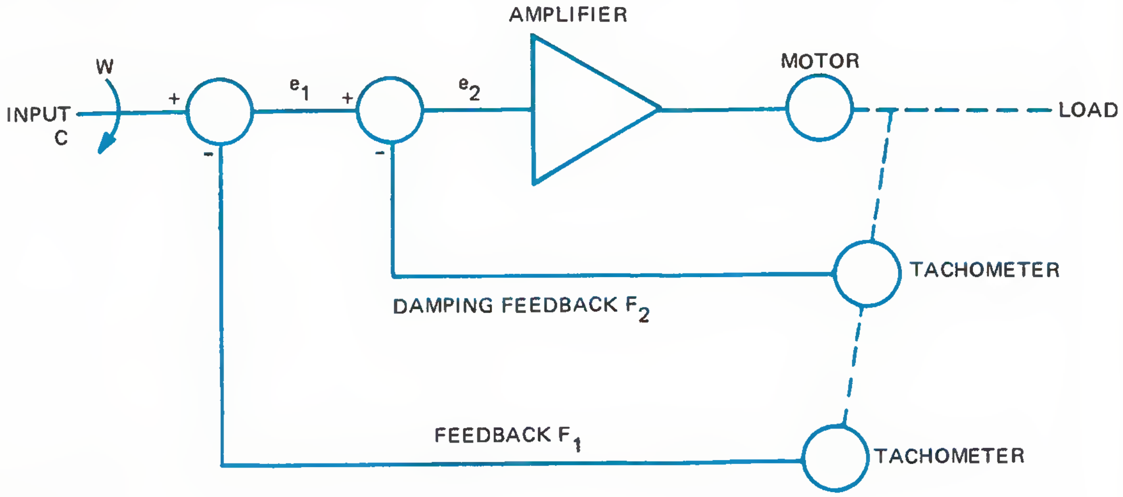


Fig. 14-8 Velocity Damping System

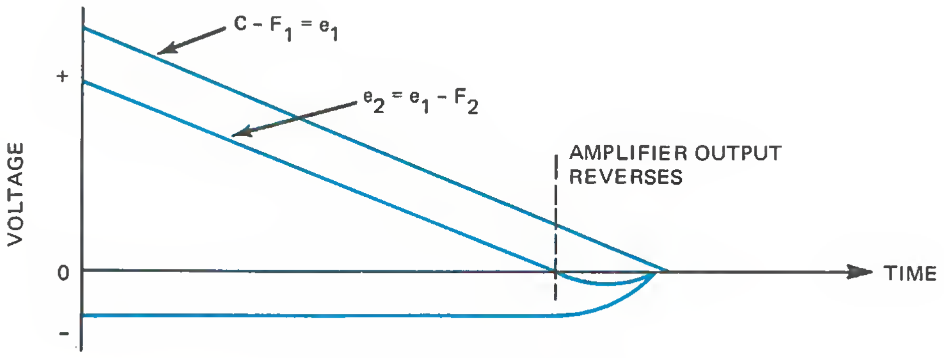


Fig. 14-9 Velocity Damping

MATERIALS

1 Audio oscillator
1 Potentiometer, 0–100 kΩ 1W
1 VOM or FEM
1 Switch, SPST
1 Motor-generator unit
Motor — 2 phase, 60 Hertz, 115/115 volts, 2 pole, 3350 RPM, 7 - 7 oz. in stall torque
Generator — 32 volts, AC, 60 Hertz separately excited output approximately 3 volts/1000 RPM
1 Dynamometer
1 Amplifier, gain of 5000 with gain control and velocity feedback provisions, input impedance 100 kΩ, output impedance 400 ohms, output power 20 watts into rated load

PROCEDURE

1. Construct the experimental circuit shown in figure 14-10.

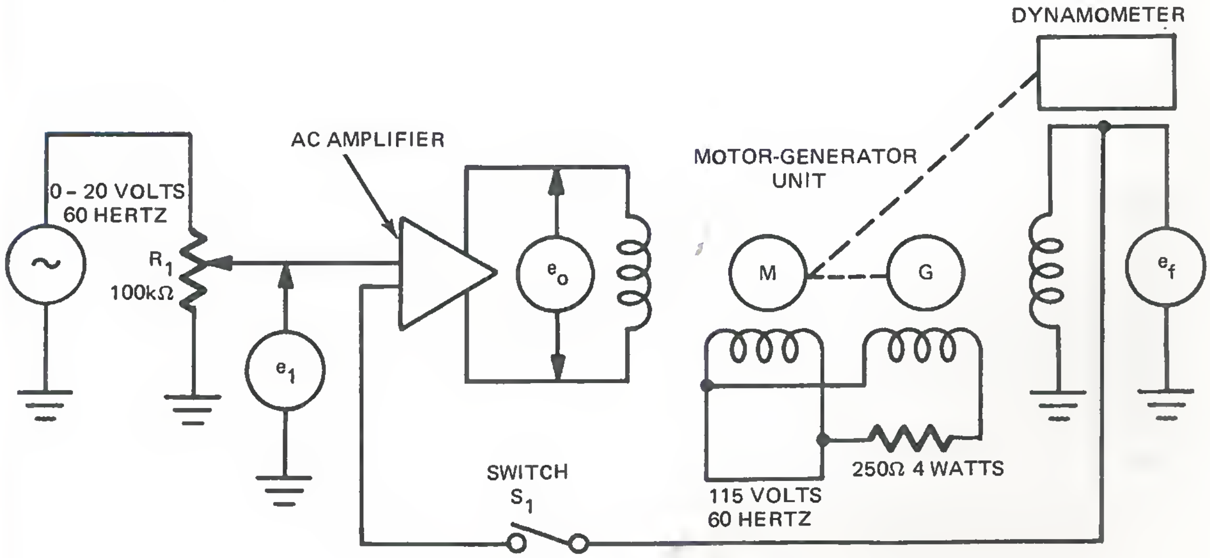


Fig. 14-10 Experimental Setup

S	e_1	e_o	e_f	A_u
500				
1000				
1500				
2000				
2500				
3000				

(A)

S	e_1	e_o	e_f	A_u
500				
1000				
1500				
2000				
2500				
3000				

(B)

S	e_1	e_o	e_f	A_u
500				
1000				
1500				
2000				
2500				
3000				

(C)

S	e_1	e_o	e_f	A_u
500				
1000				
1500				
2000				
2500				
3000				

(D)

S	e_1	e_o	e_f	A_u
500				
1000				
1500				
2000				
2500				
3000				

(E)

S	e_1	e_o	e_f	A_u
500				
1000				
1500				
2000				
2500				
3000				

(F)

Fig. 14-11 The Data Tables

2. Adjust the gain control of the AC amplifier to a minimum.
3. Set the dynanometer to apply zero torque.
4. With switch S-1 open, adjust R_1 until the speed of the motor is 500 RPM.
5. Measure the input voltage, e_1, output voltage, e_2, and generator output voltage, e_f, and record these values in the Data Table, figure 14–11A.
6. Calculate the open loop gain of the amplifier ($°o/e_i$) and record it in the Data Table as A_u.
7. Repeat steps 2 through 6 for 1000 RPM, 1500 RPM, 2000 RPM, 2500 RPM, and 3000 RPM.
8. Repeat steps 2 through 7 for the maximum amplifier gain setting.
9. Record these results in the Data Table, figure 14–11B.
10. Close switch S-1 and repeat steps 2 through 7.
11. Record your results in the Data Table, figure 14–11C.
12. Repeat step 8 with switch closed and record the results in figure 14–11D.
13. Set the gain control adjustment to one-half the maximum gain.
14. Adjust the dynanometer to provide one-half the rated torque load of the motor.
15. Repeat steps 2 through 7 and record the results in figure 14–11E.
16. Repeat step 10 for the conditions given in steps 13 and 14. Record these data in figure 14–11F.

ANALYSIS GUIDE. Plot a graph of the open loop gain (minimum gain setting) with no torque load versus RPM. On the same graph, plot the open loop gain (maximum gain setting), closed loop gain (minimum gain setting), and closed loop gain (maximum gain setting) versus RPM. Plot a graph of the open loop gain (one-half maximum gain setting) with one-half rated torque load versus RPM. On the same graph, plot the closed loop gain (one-half maximum gain setting) with one-half rated torque load versus RPM.

PROBLEMS

1. Calculate the output speed of a velocity control system that is similar to the one in figure 14–1. The amplifier is linear and has a gain of 50. The actuator has a rating of 200 RPM/volt and the tachometer generator, 2 volts/100 RPM. The gear box between the motor and tachogenerator has a ratio of 2 to 1.
2. Calculate the control gain of the system in problem 1.
3. How would you increase the accuracy of the system in problem 1?
4. How could you use two separately-excited DC generators as a two-stage amplifier?

experiment 15 PROCESS CONTROL SYSTEMS

INTRODUCTION. A process is an operation or series of operations on fluid (liquid and gas) or solid materials during which the materials are placed in a more useful state. In this experiment, the methods of process control will be investigated.

DISCUSSION. The development of process controls and servomechanisms proceeded, with time, along quite separate routes using different terminology. As a result, it was some time before the various technological personnel realized they were all saying the same things in different languages. The electromechanical technician of today is able to study the theory and applications of closed loop systems in general with a full realization that the general properties or concepts are common to all. When working with an automatic control system, whether a process or a servomechanism, the first step is to identify the variable to be controlled, the sensing or measuring element, the reference or set-point, the method of error generation, the controller or amplifier, and the actuator that controls the manipulated variable. The second step is to determine the type of control action (on-off, proportional, proportional-plus-reset, proportional-plus-reset-plus-rate). The third step is to study the system until you understand its overall function or operation. The last step, before you start to work, is to ask yourself: What significant properties of the system can I test? Which of these properties should I test and in what sequence? How do I test these properties and what type of measuring equipment is required?

Process control is concerned with maintaining the controlled variable at a desired level. The controlled variable of a process may be temperature, pressure, flow, liquid-level, pH factor, density or any other physical quantity. As with a servomechanism or velocity control system, the control action is dependent on the deviation of the controlled variable from the desired value. It is the function of the automatic process control system to keep the deviation to a minimum and to return the controlled variable to its desired value as quickly as possible following a command or a load change. Over-sensitivity, delayed response, or instability may have an adverse effect on the performance of the system.

The controlled variable of the process should be that variable which most directly indicates the desired form or state of the product. Direct control of the controlled varaible would most likely insure satisfactory performance and maintain the process closer to the desired value.

A hot water tank is shown in figure 15–1. The purpose of the hot water tank is to supply heated water. The controlled variable, in this case, would be the temperature of the water at the tank outlet. The manipulated variable would be the heat flow, because it is relatively easy to manipulate. The load variables, in this case, are all the other variables in the system. Two of these load variables are the incoming water temperature and the output flow rate.

In some systems, it is difficult to control the actual process variable directly: therefore, a secondary variable of the process may be controlled. This form of control is termed

indirect control. For example, a furnace used in the preparation of sand castings is designed to produce properly baked sand castings, and therefore, the controlled variable should be the baked condition of the sand. However, the baked condition of the casting is not easily determined without destroying the casting and it is more convenient to select furnace temperature as the controlled variable. The baked condition of the sand casting is directly related to the furnace temperature.

A system will require a definite time to change the controlled variable when a commanded step change is initiated. The maximum rate of change of the controlled variable following a specified step change is termed the process reaction rate. Whatever the process, the capacitance of the system has the effect of delaying process reaction rate. The reciprocal of the reaction rate is the capacitive lag.

The dead time or distance velocity lag is the delay due to the transmission distance, or to the time it takes for the process to begin. For example, the pneumatic system shown in figure 15–2 has its pump installed in the basement of a 10-story building with the pressure transducer mounted on the tenth floor. If the pump outlet pressure is increased, a short time will have elapsed before the pressure on the tenth floor changes. This delay is called the dead time or distance velocity lag. The dead time of a chemical reaction is the time that must elapse before the reaction begins to occur.

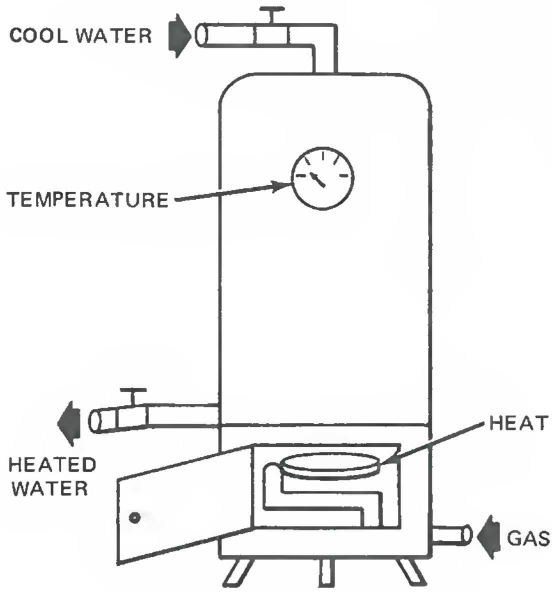


Fig. 15-1 Thermal Process

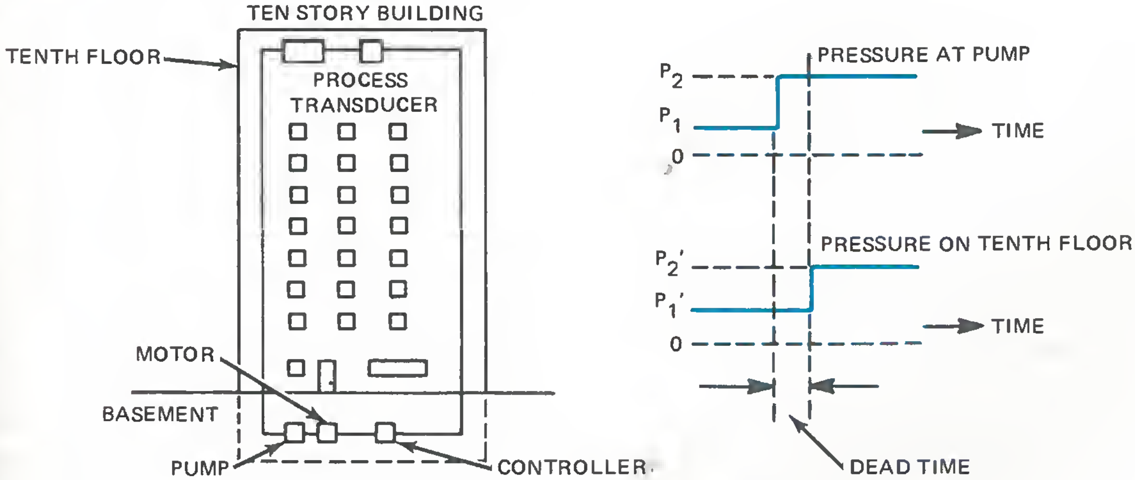


Fig. 15-2 Pressure System Dead Time

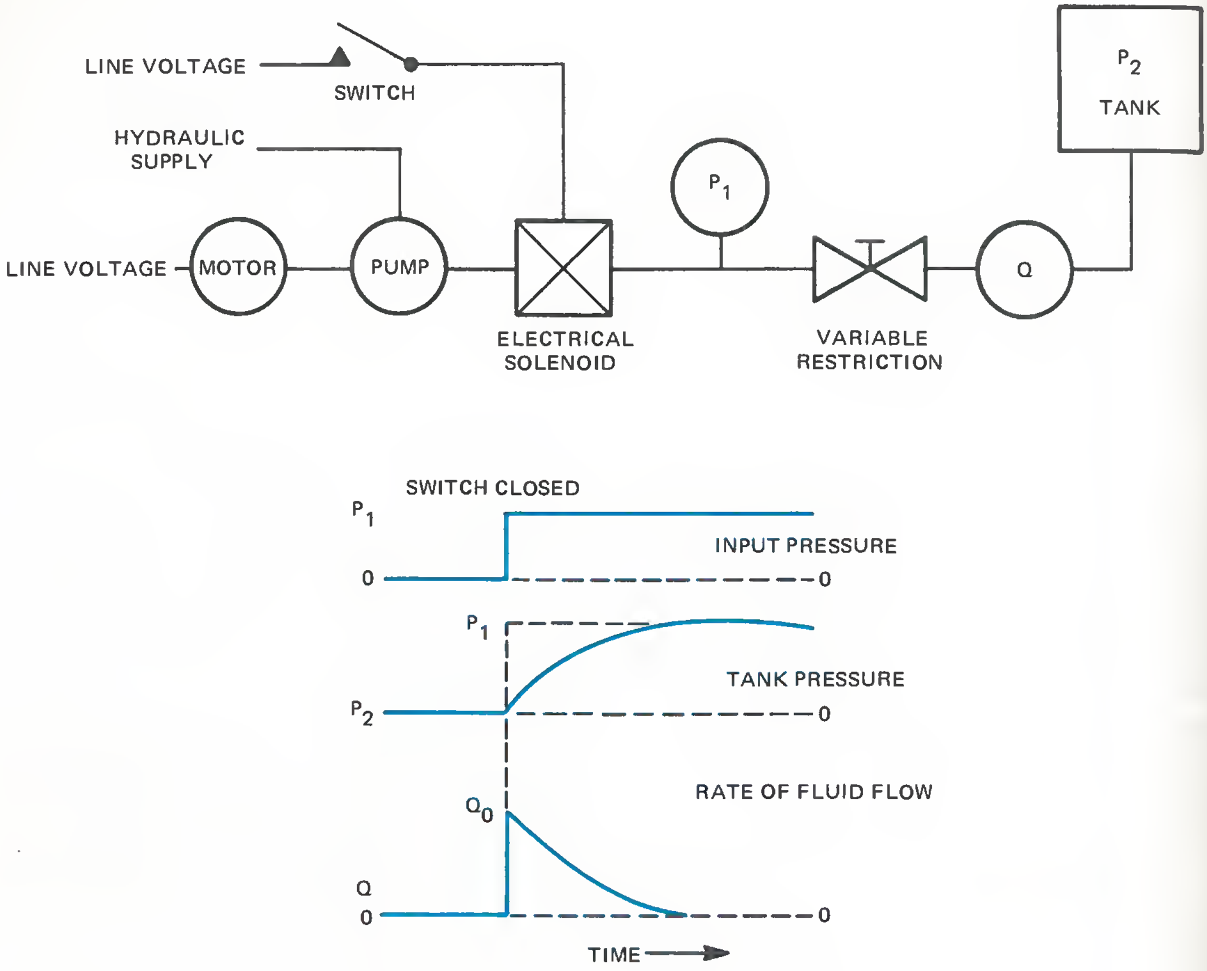


Fig. 15-3 Hydraulic System Transfer Lag

A transfer lag occurs whenever energy is transferred to or from a capacitive element through a restriction. In electrical circuits, the transfer lag is termed the phase angle. It is the angle between the input and output quantities. Similarly, thermal, fluid, and mechanical systems also exhibit transfer lags. For example, a transfer lag results from the thermal resistance between the heating element and the process combined with the capacitance of the process in a temperature control system. Figure 15-3 shows a hydraulic system and its response illustrating transfer lag.

The control action of a process system may be on-off, proportional, integral, derivative or a combination of these actions. As with other systems using proportional control, its inability to accommodate load changes causes a sustained deviation known as *offset.*

The proportional band of a controller is that percentage of the controller scale required to vary the output over its full range. For example, a pneumatic temperature controller with a total range of 0 - 500°C has its gain (sensitivity) set so that its full output range, 5 - 25 psi; is covered for a temperature deviation about the set-point of ±50°C. Therefore, the controller's proportional band is 100°/500° X 100 = 20%.

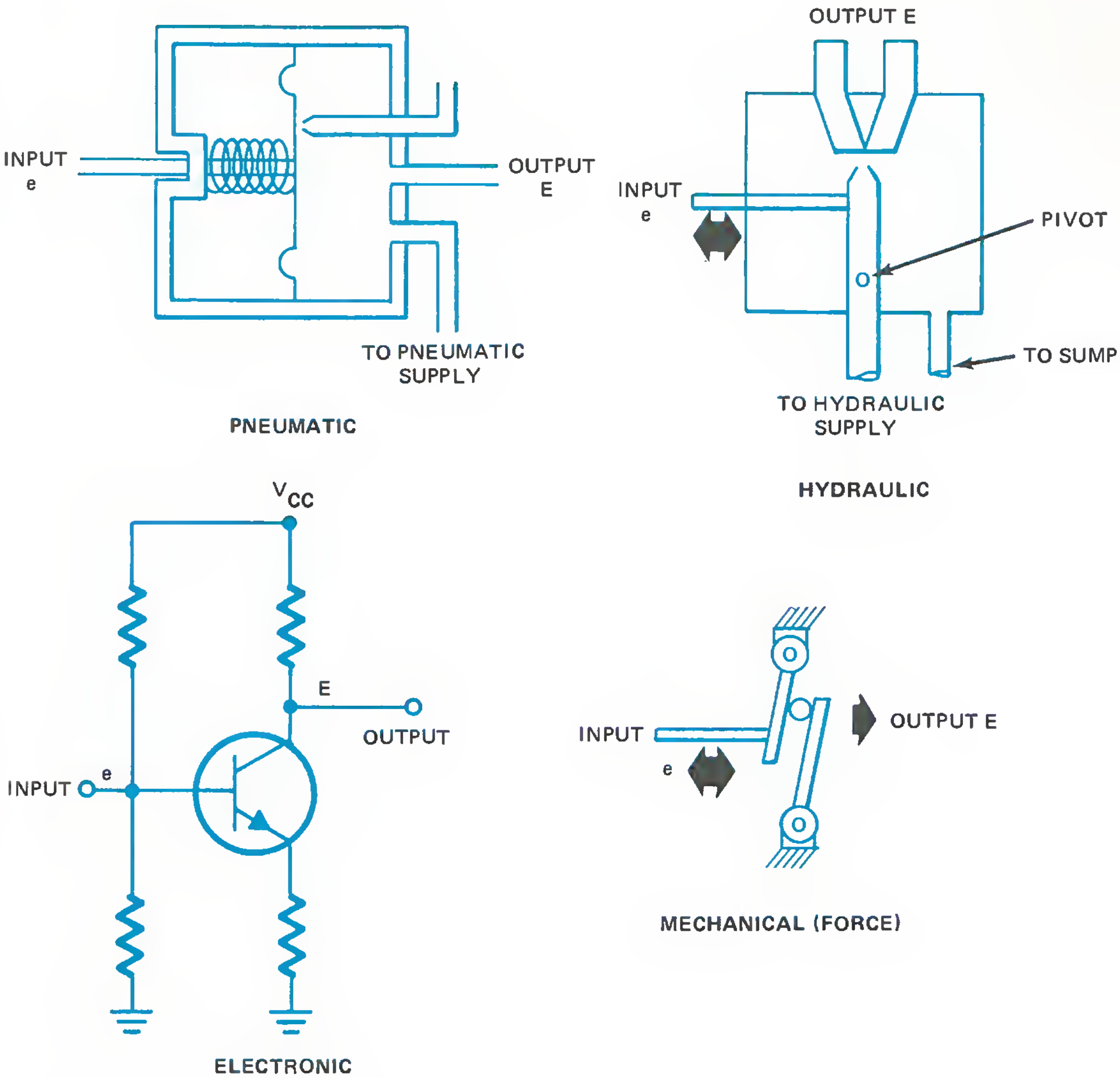


Fig. 15-4 Process Controllers

The gain of the process controllers shown in figure 15-4 is usually measured as the ratio of the change in output to the corresponding change in input. Expressed mathematically

$$K_c = \frac{\Delta \text{ output}}{\Delta \text{ input}} = \frac{\Delta E}{\Delta e} \qquad (15.1)$$

In the case of an electronic amplifier, the output and input quantities are in the same units, therefore, its gain is a dimensionless number. In other processes, the controller's input and output may be in different units and are not as easy to recognize. For example, a flapper and nozzle amplifier in a pneumatic system has an input flapper-to-nozzle clearance in inches, while the output is pressure in psi; therefore, the gain units may be psi/inch.

Another method of determining the gain which avoids the use of dimensions is to express the change in both the input and output as percentages. Consider the pneumatic temperature controller cited previously. The percentage of full range outpot, 5 – 25 psi, to the

full range available for use, 5 - 25 psi, is 100%, while the controller's proportional band (input expressed as a percentage) was calculated as 20%. Therefore, the gain of this pneumatic controller is

$$K_c = \frac{\text{output expressed as a percentage}}{\text{corresponding change in input expressed as a percentage}}$$

$$K_c = \frac{100\%}{20\%} = 5 \qquad (15.2)$$

The actuator gain of a process system may also be determined using equation 15.2. Consider an actuator whose full range is 5 - 25 psi and the output of the controller changes the pressure output of the actuator from 5 - 25 psi. The output expressed as a percentage is 100%. The full output of the controller is required to produce the full output of the actuator, and the input (output of the controller) to the actuator expressed as a percentage is 100%. Therefore, the gain of the actuator is 100%/100% = 1. A different actuator with the same output range of 5 - 25 psi requires an input pressure of 10 - 15 psi to produce the full output. The gain of this actuator is 100%/25% = 4.

Testing process systems for frequency response and transient response is much the same as testing for a servomechanism or speed control. The sinusoidal input of obtaining the frequency response of a process system should be reasonable free from harmonics. The sinusoidal signal may be in the form of a mechanical, pneumatic, thermal or electrical variation. The frequency of such test signals is usually approximately as follows:

Fluid processes	0.005 to 10.0 Hz
Thermal processes	0.001 to 1.0 Hz
Process control mechanisms	0.01 to 100 Hz

Below 0.01 Hz, a mechanical generator consisting of a variable speed drive and a suitable pneumatic, electrical, or hydraulic transducer is employed. Above 0.01 Hz an audio oscillator or function generator is employed with a suitable transducer. The recording of input and output signals is usually done with a chart recorder.

Stability of operation of the process is achieved when the deviation is maintained within predetermined limits. Stability and/or transient response is usually tested using a step input. The offset is determined using a ramp function.

Figure 15-5 shows a pressure-controlled roller for pressing wood into a thin sheet. The roll bearing pressure is transmitted through a load cell to a strain gage. Movement of the load cell deflects the strain gage, which in turn, changes its electrical resistance.

The change in electrical resistance will cause a deviation to exist between the set-point and the input from the strain gage. The controller amplifies this deviation and drives the directional valve. The directional valve controls the amount of pressure and the direction of the fulid pressure within the cylinder.

The cylinder will increase or decrease the force exerted by the roller until the output of the strain gage is equal to the set-point. When this balance is attained, the force exerted by the cylinder on the roller is maintained. If more or less pressure on the wood sheet is desired, the set-point must be changed.

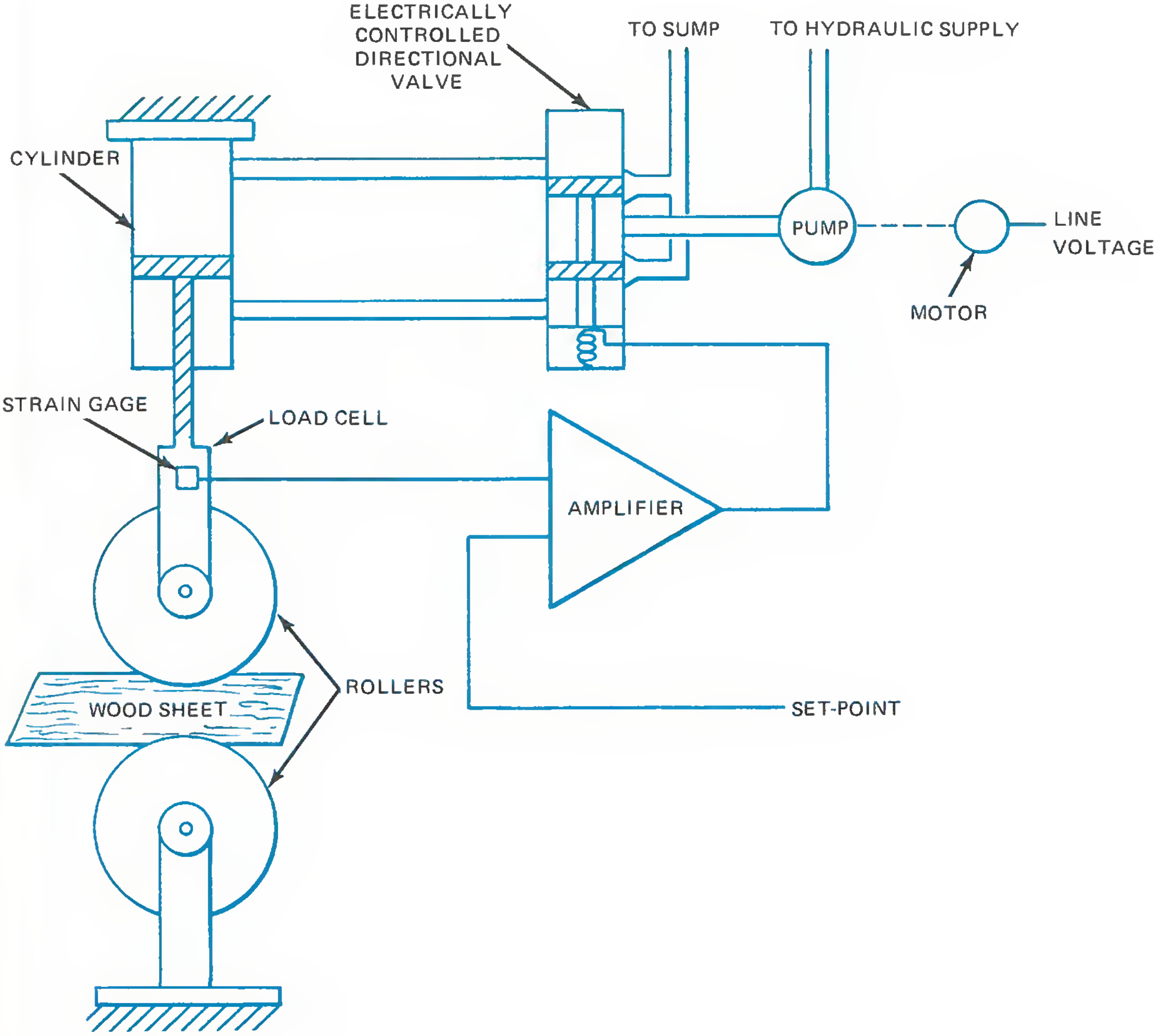


Fig. 15-5 Control of Pressure on a Pressed-Wood Sheet

MATERIALS

1 SCR, GE type 106B or equivalent
2 UJT, GE type 2N2646 or equivalent
1 Zener diode, 12 volts
1 Diode, 1N4148 or equivalent
1 Thermistor, 5 kΩ at 25°C
1 Heater, 150 watts, 115 volts, 60 Hz
1 Resistor, 6.8 kΩ, 2W
1 Resistor, 1 kΩ, 1W
1 Resistor, 47Ω, 1W
1 Potentiometer, 10 kΩ, 1W
1 Capacitor, 0.02 μF
1 Thermocouple bridge, 0 - 200° F
1 Circular chart recorder, 96 min/revolution, 50 - 200° F
1 Switch SPST
2 VOM or FEM
1 AC ammeter, 0 - 2 amps
1 Container, 5 gal

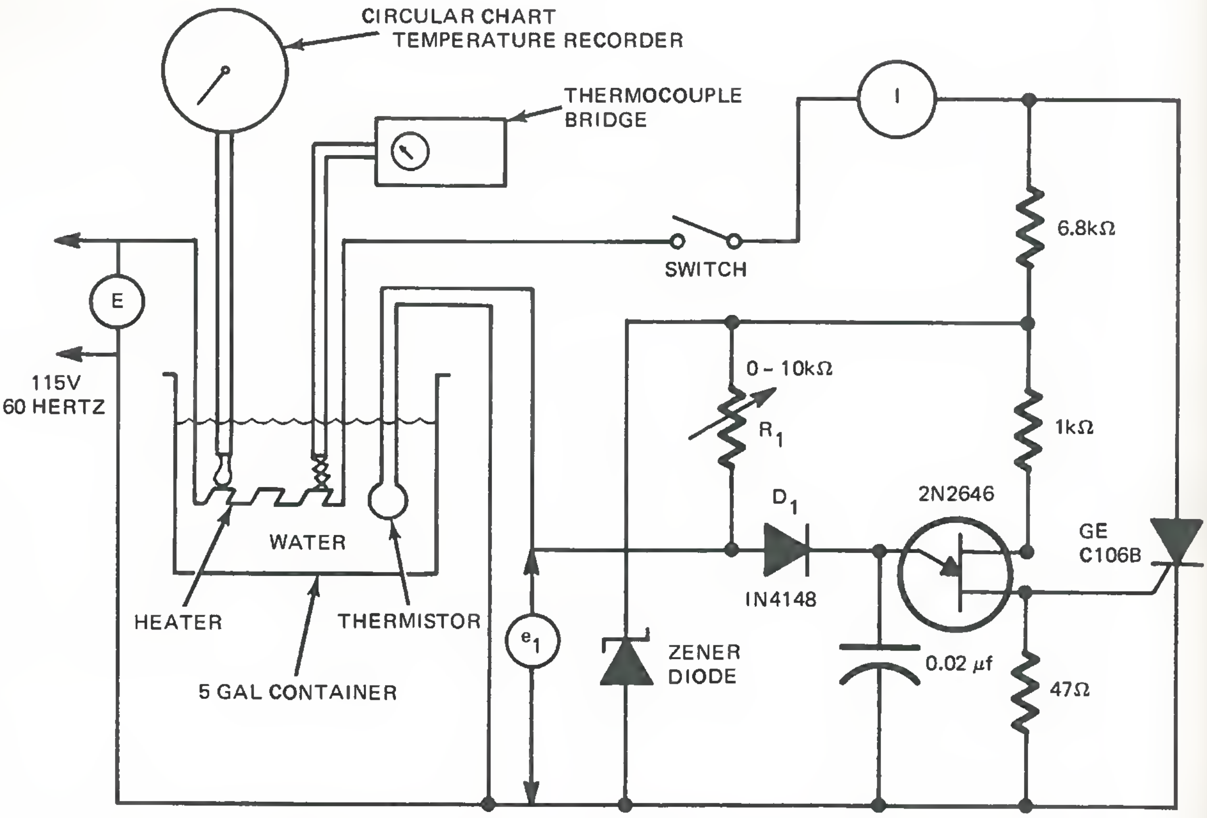


Fig. 15-6 Experimental Circuit

PROCEDURE

1. Connect the circuit as shown in figure 15-6.
2. Pour one-half gallon of water in container.
3. Measure the temperature of the water with the termocouple bridge.
4. Record the value as T in the Data Table, figure 15-7A.
5. With R_1 set at 2.5 kΩ, close the switch and measure the temperature, heater current, line voltage, thermistor voltage, and time as the temperature increases.
6. Record these values in figure 15-7A as T, I, C, e_1 and t respectively.
7. Measure and record the values in step 5 for two or three cycles of temperature variation.
8. Calculate the product EI for each case. This quantity is proportional to the heat of the heater. Record it as h in the Data Table.
9. Suddenly change R_1 to 5 kΩ (simulating a step input in command).
10. Repeat steps 5 through 7.
11. Record these data in figure 15-7B.

12. Pour another one-half gallon of cool water into the container (simulating a step input in load).
13. Repeat steps 5 through 7.
14. Record the data in figure 15-7C.

T	e_1	t	E	I	h

(A)

T	e_1	t	E	I	h

(B)

T	e_1	t	E	I	h

(C)

Fig. 15-7 The Data Tables

ANALYSIS GUIDE. Plot a graph of temperature versus time, heat (h) versus time, and e_1 versus time. The graph should show the response due to a command change and also the response to a load change. Compare the plotted data with the data contained on the circular chart.

PROBLEMS

1. Define the terms, automatic control, process control and servomechanism.
2. Draw a general block diagram of a process control system and a servomechanism.
3. Calculate the proportional band of a hydraulic controller that has a total range of 0 - 2000 psi with its set-point at 500 psi. A deviation of ± 100 psi will cause the output of the controller to vary from 0 to 1000 psi.
4. Determine the gain of the controller in problem 3.
5. Draw a schematic of an automatic control system that is capable of maintaining the temperature of a refrigerator at any desired setting from 0° to 30° F. Explain your system's operation.

EXPERIMENT 1 ______________ Name ______________________________

Date: ______________________ Class __________ Instructor ______________

R inches	S_a RPM	S_o RPM	T in.-oz	% Change in S_a	% Change in S_o
	1000	1000		0	0
1.50			1.50		

Fig. 1-7 The Data Table

EXPERIMENT 2 ______________ Name ______________________________

Date: ______________________ Class ___________ Instructor ______________

Position in Degrees	Resistance		
	A to B	A to C	B to C
0°			

Steps 4-6 Results

Fig. 2-14A The Data Table

Position in Degrees	Voltage		
	A to B	A to C	B to C
0°			

Step 9 Results

Fig. 2-14B The Data Table

Position in Degrees	Voltage		
	V_{BC}	V_{ED}	V_{DC}
0°			

Step 11 Results

Fig. 2-14C The Data Table

EXPERIMENT 3 Name ____________

Date: ____________ Class ____________ Instructor ____________

90°F Setting		
Temp. (°F)	Pressure (psi)	Time
79		
80		
81		
82		
83		
84		
85		
86		
87		
88		
89		
90		
91		
92		
93		
92		
91		
90		
89		
88		

90°F Setting		
Temp. (°F)	Pressure (psi)	Time
89		
90		
91		
92		
93		
92		
91		
90		
89		
88		
89		
90		
91		
92		
93		
92		
91		
90		
89		
88		

Fig. 3-5 The Data Table 90° F

80°F Setting		
Temp. (°F)	Pressure	Time
79		
80		
81		
80		
79		
80		
81		
80		
79		
80		
81		
80		
79		

Fig. 3-6 The Data Table 80°F

EXPERIMENT 4 Name ______________________

Date: ______________ Class ________ Instructor ____________

Pressure psi	Deflection in cm	F_R in lbs	F_L in lbs
0	0		
10			
10			
20			
30			
40			
50			
60			
70			
80			
90			

Fig. 4-11 The Data Table

EXPERIMENT 5 Name ____________________

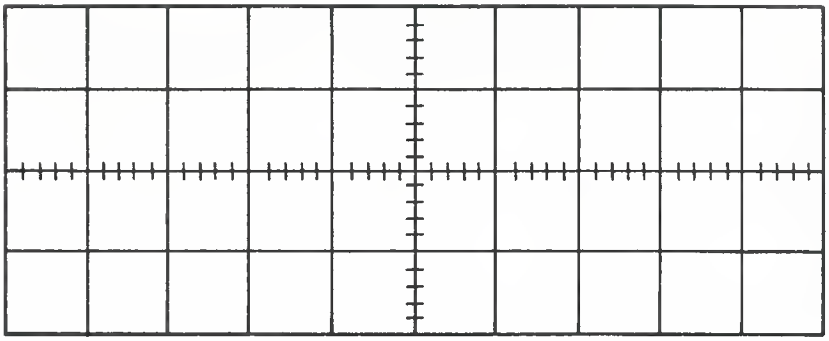
Date: ____________ Class __________ Instructor ____________

Input Voltage	+2 DC	+1 DC	+0.5 DC	0 DC	-0.5 DC	-1.5 DC	-2 DC	+2 PK
Impedance Matching Stage Gain								
Preamplifier Stage Gain								
System Gain								

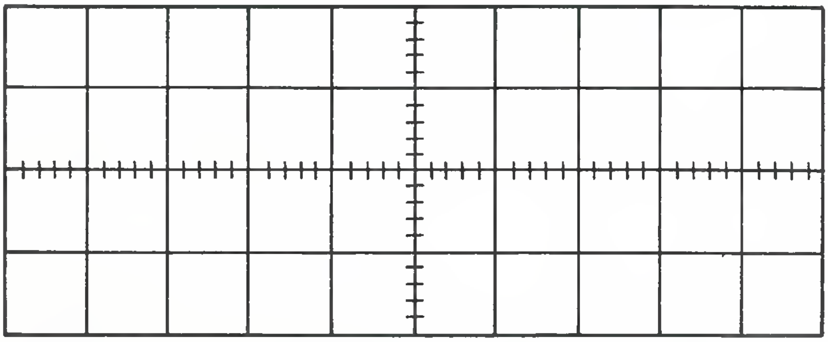
Fig. 5-13 The Data Table

Procedure step 4: (DC input = + 2V)

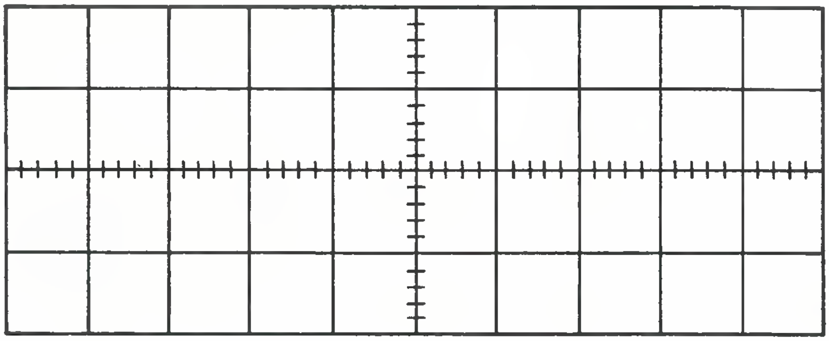
A TO GROUND



B TO GROUND



C TO GROUND



D TO GROUND

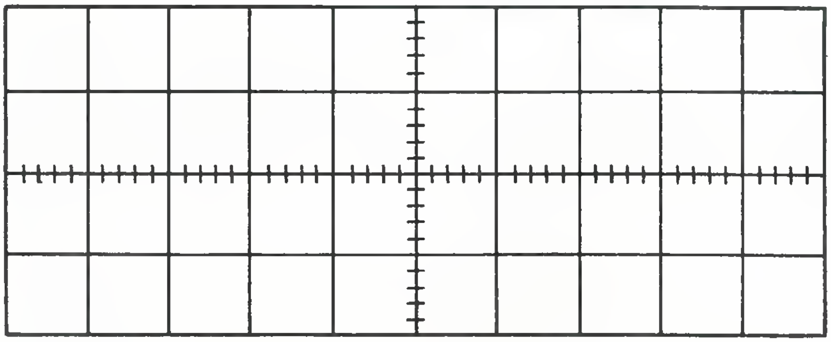


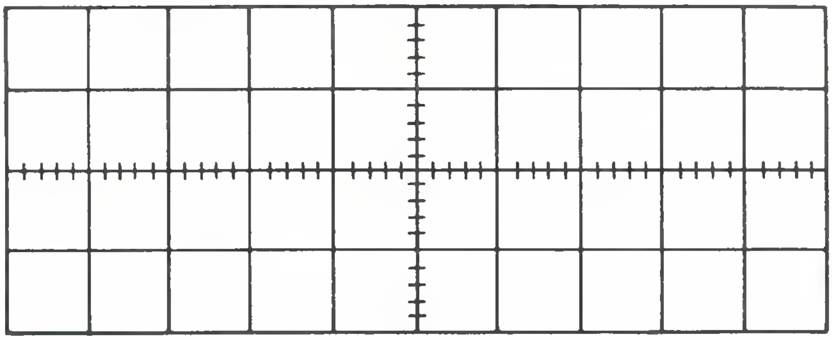
Fig. 5-14 The Results

EXPERIMENT 5 Name ______________________

Date: ______________ Class __________ Instructor ______________

Procedure step 5: (DC input of 1.0V)

A TO GROUND



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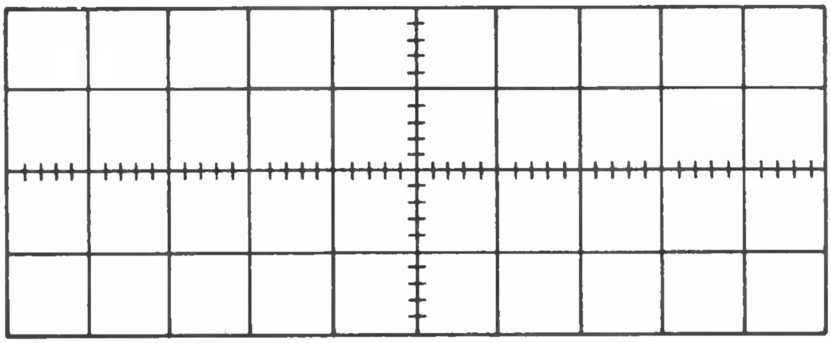

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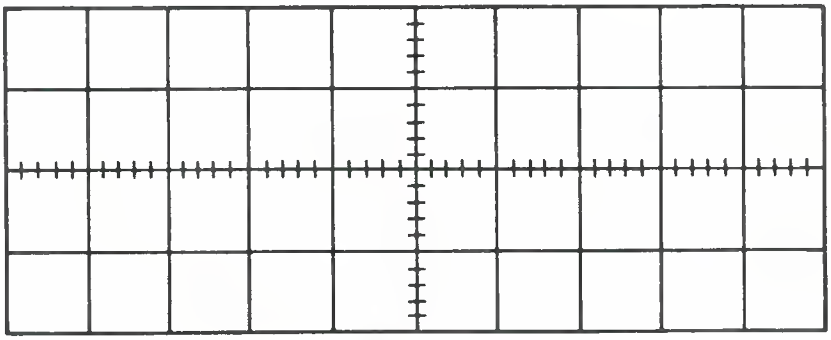

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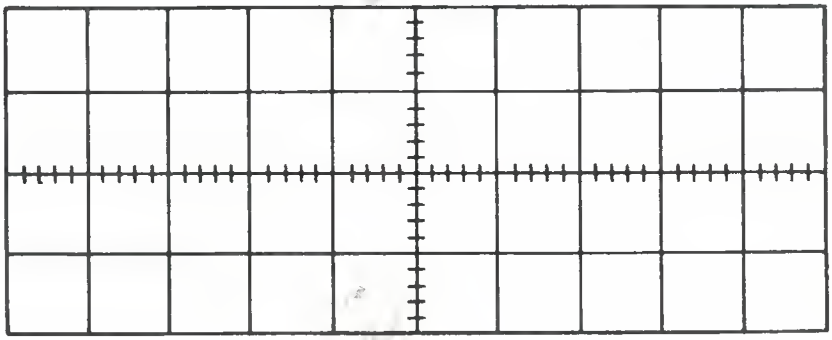
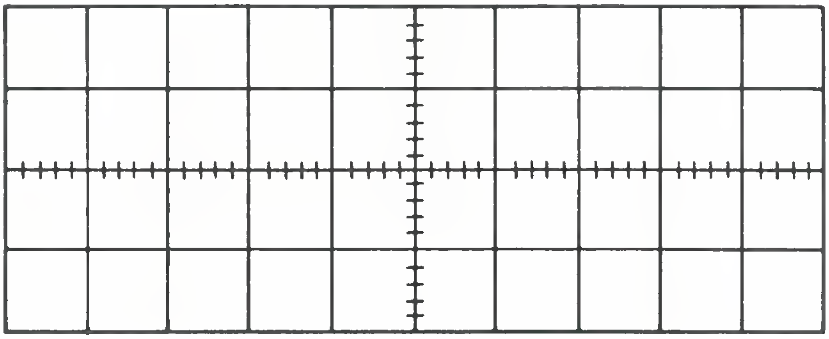


Fig. 5-14 The Results (Cont'd)

Procedure step 5: (DC input = 0.5V)

A TO GROUND



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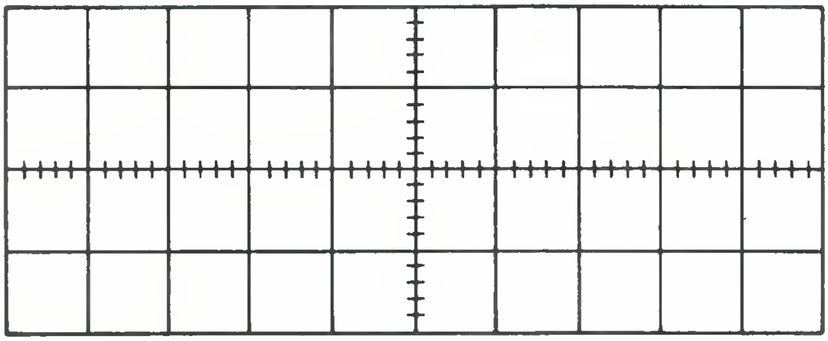

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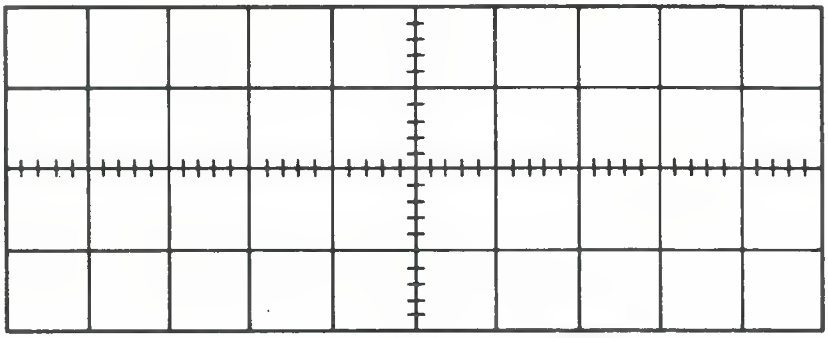

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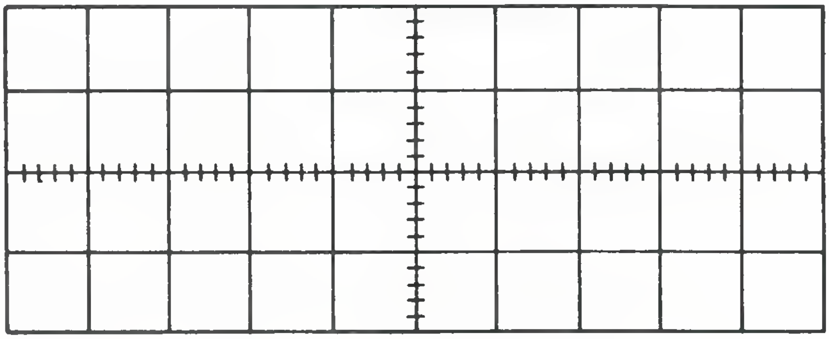


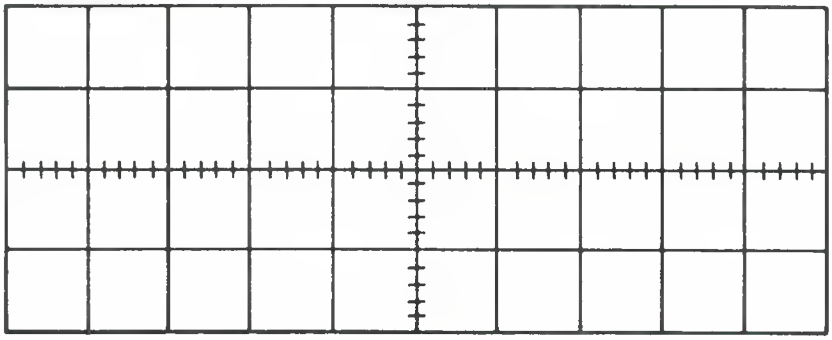
Fig. 5-14 The Results (Cont'd)

EXPERIMENT 5 Name ______________________________

Date: ____________________ Class __________ Instructor ______________

Procedure step 5: (DC input = 0V)

A TO GROUND



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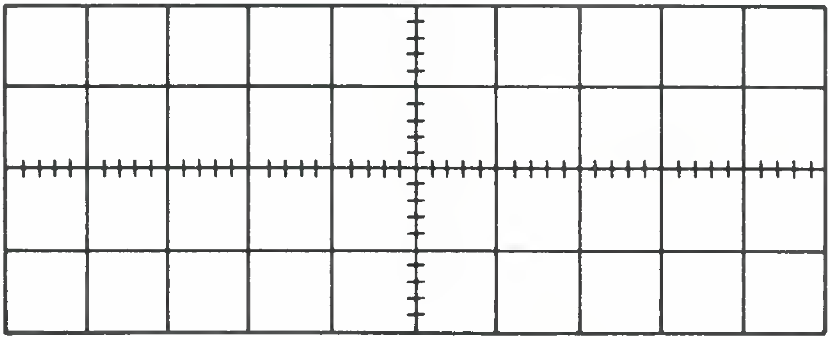

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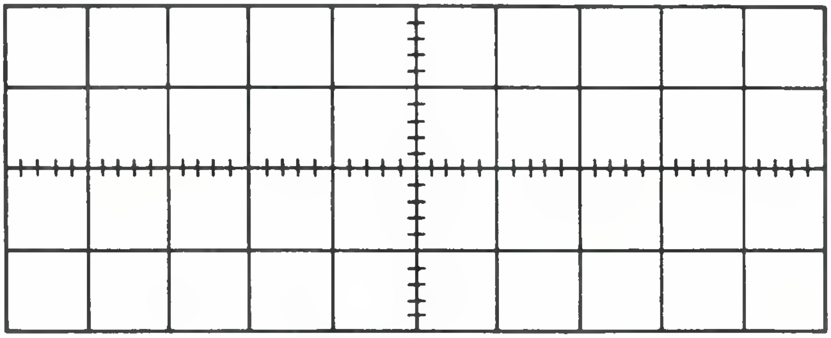

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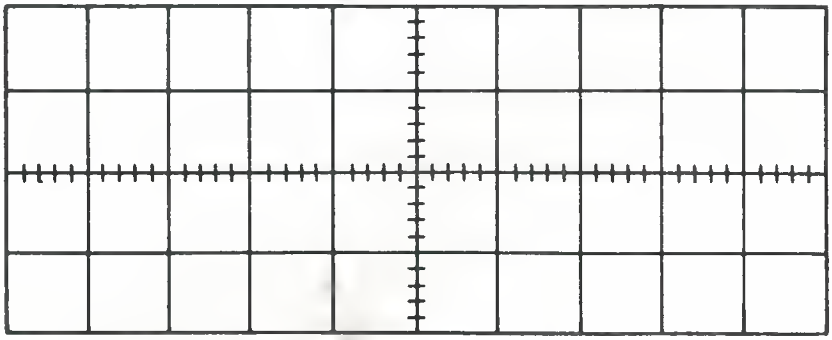
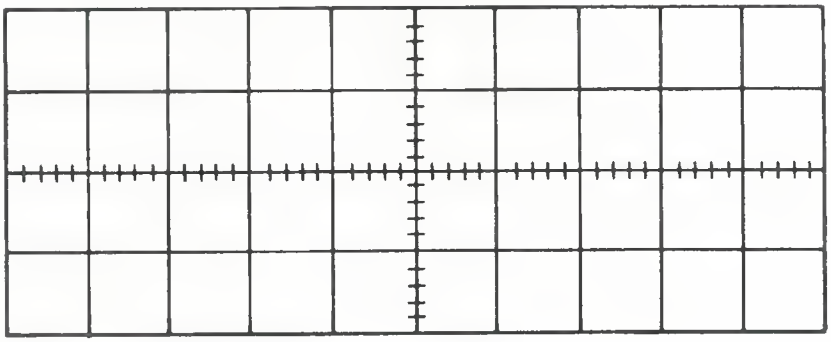


Fig. 5-14 The Results (Cont'd)

Procedure step 5: (DC input = –0.5V)

A TO GROUND



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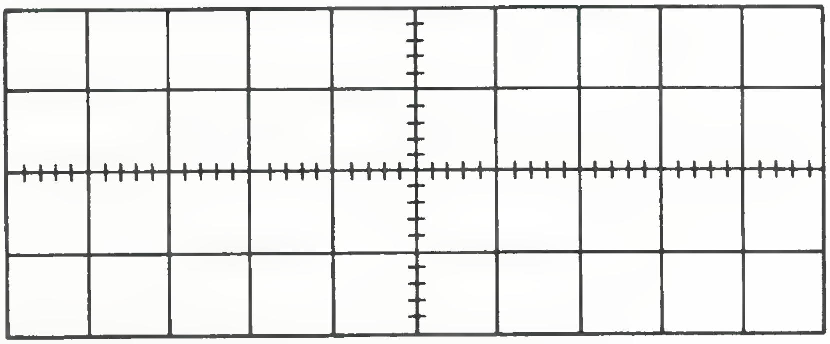

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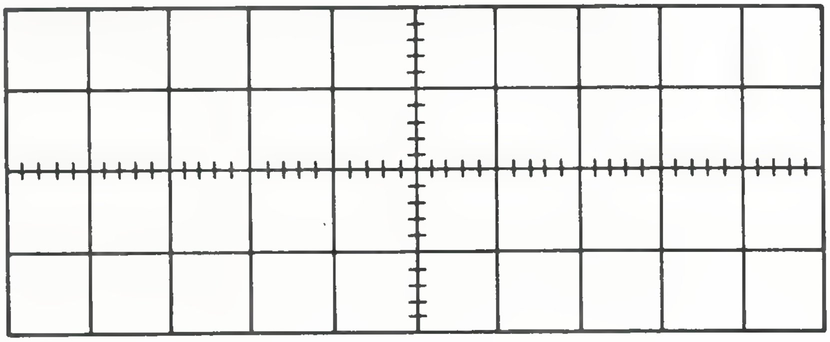

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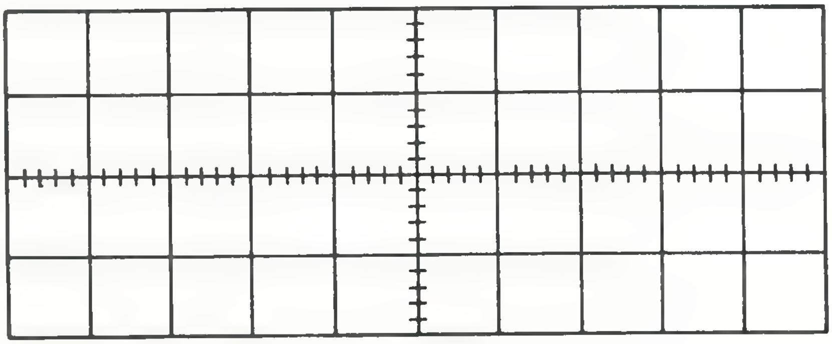


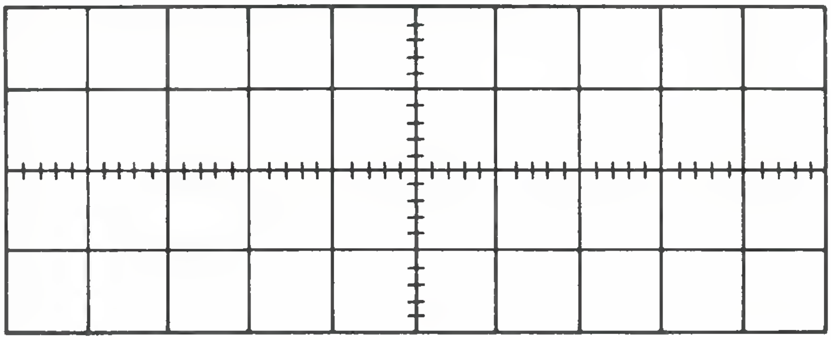
Fig. 5-14 The Results (Cont'd)

EXPERIMENT 5 Name ____________________

Date: ____________________ Class ____________ Instructor ____________________

Procedure step 5: (DC input = −1.5V)

A TO GROUND



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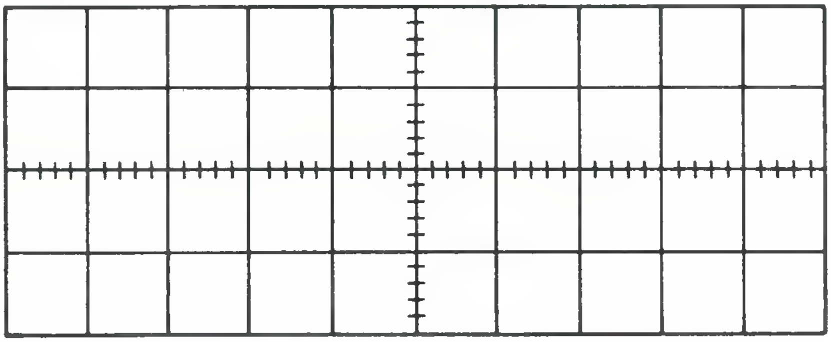

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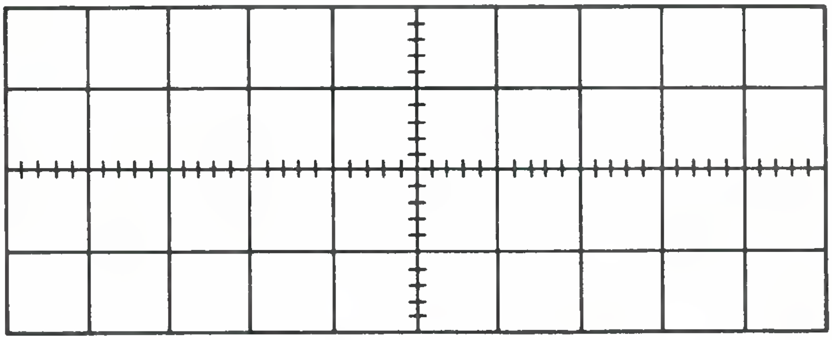

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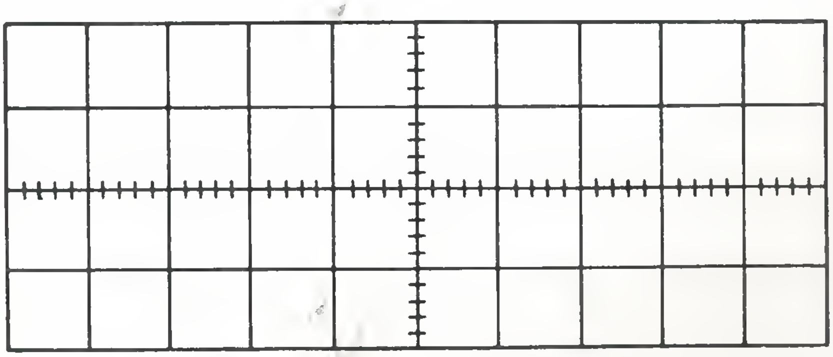
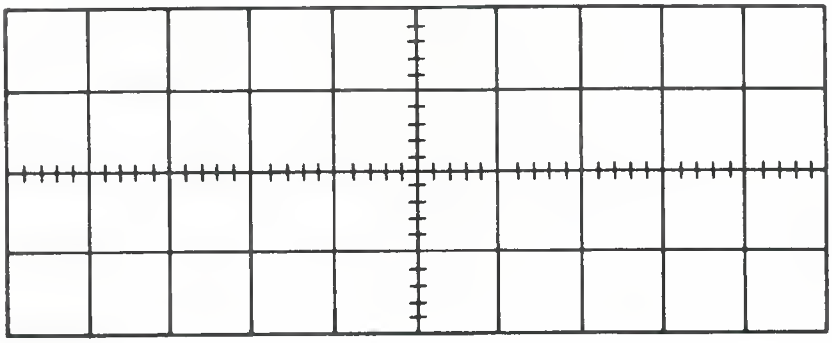


Fig. 5-14 The Results (Cont'd)

Procedure step 5: (DC input = -2.0V)

A TO GROUND



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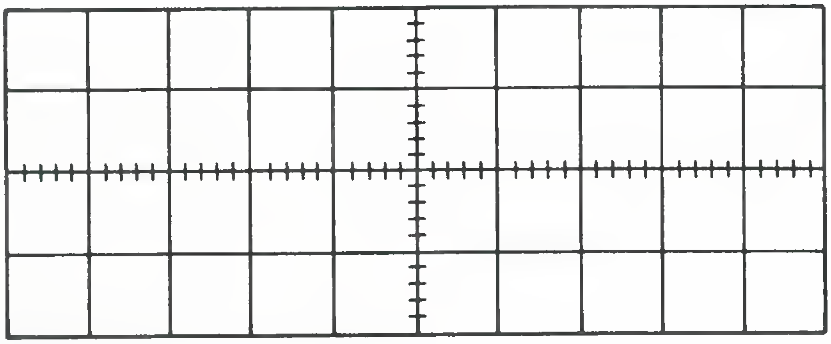

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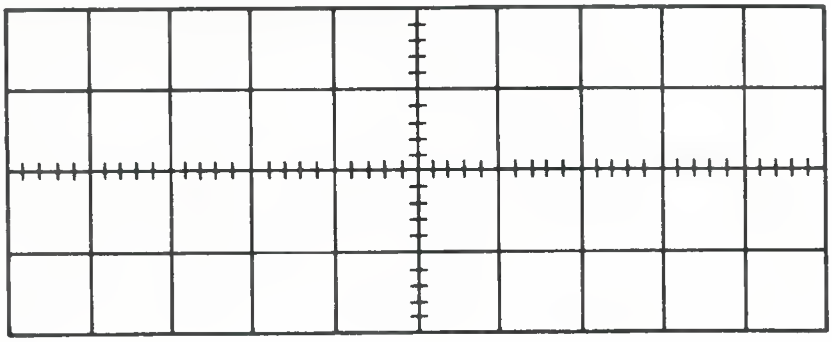

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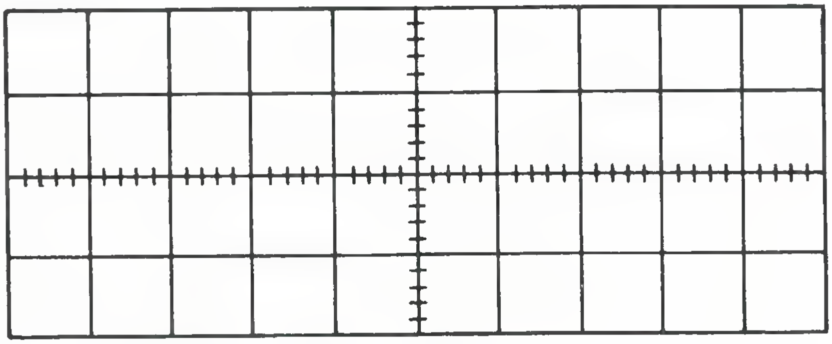


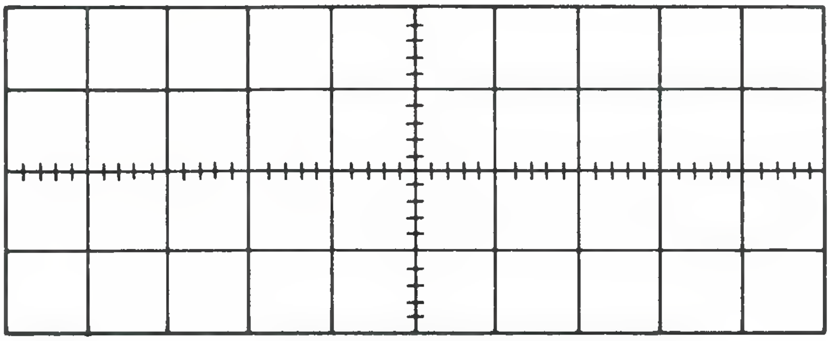
Fig. 5-14 The Results (Cont'd)

EXPERIMENT 5 Name ______________________

Date: ______________ Class __________ Instructor ______________

Procedure step 11: (AC input = 2 volts peak at 20 Hz)

A TO GROUND



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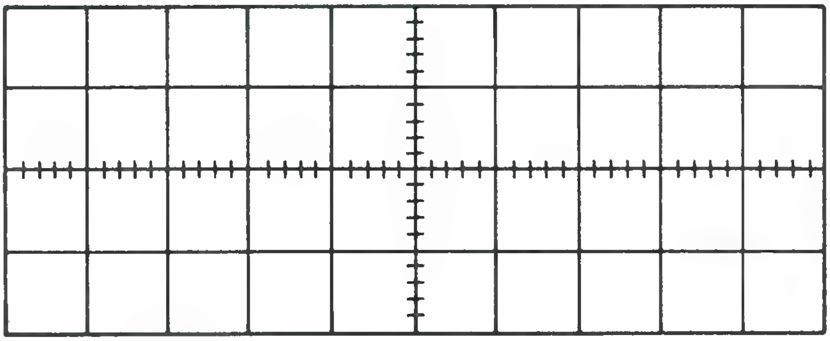

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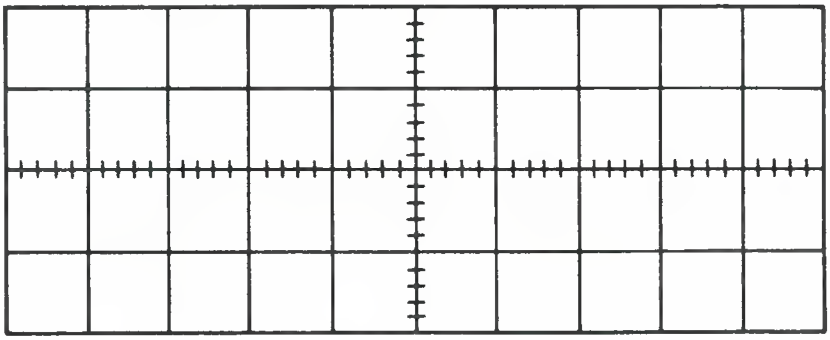

D TO GROUND

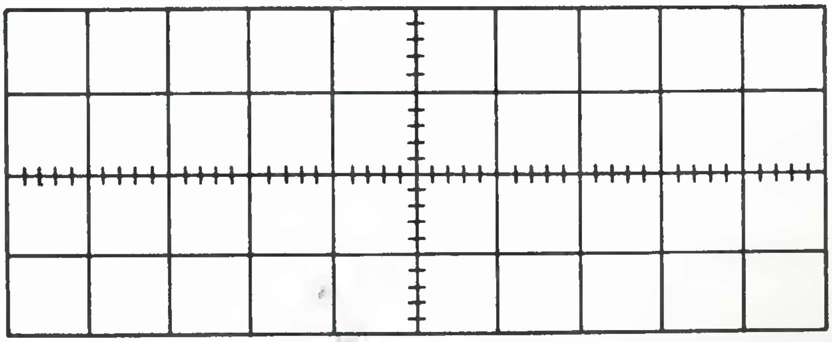

Fig. 5-14 The Results (Cont'd)

EXPERIMENT 6 Name ____________________

Date: ____________ Class ________ Instructor ____________

f_x	f_1	f_{in}	f_{out}	A_f	P_1	P_2
		0 grams	0 grams	0	15 psi	0
					15 psi	
					15 psi	
					15 psi	
					15 psi	
					15 psi	
					15 psi	
					15 psi	
					15 psi	
					15 psi	

Fig. 6-9 The Data Table

EXPERIMENT 7 Name ______________________

Date: ______________ Class __________ Instructor ______________

d	w
0 inch	0 pounds
0.25	
0.50	
0.75	
1.00	
1.25	
1.50	
1.75	
2.00	

Fig. 7-8 Spring Data

d	P_2	P_3	ΔP	F
0 in.			0 psi	0 lbs
+0.5				
+1.0				
+1.5				
+2.0				
-0.5				
-1.0				
-1.5				
-2.0				

Fig. 7-9 Data Table II 20 psi

EXPERIMENT 8 Name ______________________

Date: ______________ Class ____________ Instructor ______________

R_f	R_c	V_c	V_1	V_2	I_c	I_f	P_c	P_f	t	S_1	S_2	Rotation Direction
		5										
		10										
		15										
		20										
		25										
		30										
		35										
		40										

Fig. 8-10 Two-Phase Motor Data

EXPERIMENT 9 Name ______________________

Date: ______________________ Class __________ Instructor ______________

1/5 Rated Torque

RPM	Q gal/min	psi	P_1 HP	P_o HP	Eff
500					
1000					
1500					
2000					

2/5 Rated Torque

RPM	Q gal/min	psi	P_1 HP	P_o HP	Eff
500					
1000					
1500					
2000					

3/5 Rated Torque

RPM	Q gal/min	psi	P_1 HP	P_o HP	Eff
500					
1000					
1500					
2000					

Fig. 9-10 The Data Tables

EXPERIMENT 10 ______________ Name ______________________________

Date: ______________________________ Class __________ Instructor ______________

Control Transmitter		Control Transformer			
Mechanical Input	Direction of Shaft Rotation	Mechanical Input	Direction of Shaft Rotation	Voltage Output	Phase
0°	–	0°	–		
5°	CW	0°	–		
10°	CW	0°	–		
15°	CW	0°	–		
15°	CW	5°	CW		
15°	CW	10°	CW		
15°	CW	15°	CW		
0°	–	0°	–		
5°	CCW	0°	–		
10°	CCW	0°	–		
15°	CCW	0°	–		
15°	CCW	5°	CCW		
15°	CCW	10°	CCW		
15°	CCW	15°	CCW		
5°	CCW	5°	CW		
5°	CW	5°	CCW		
180°	–	180°	–		
185°	CW	180°	–		
185°	CW	185°	CW		
180°	–	180°	–		
175°	CCW	180°	–		
175°	CCW	175°	CCW		

Fig. 10-18 The Data Table

EXPERIMENT 11 Name ______________________

Date: ______________ Class __________ Instructor ______________

Step 13: Receiver Action ____

____

Step 15: ____

____

____

Step 18: ____

____

Fig. 11-13 The Observed Results

EXPERIMENT 12 Name ______________________

Date: ______________ Class __________ Instructor ______________

Freq.	V_1/cm	V_1	V_2/cm	V_2	A_v	θ
1 Hertz						
3 Hertz						
5 Hertz						
10 Hertz						
15 Hertz						
25 Hertz						
40 Hertz						
60 Hertz						

Fig. 12-18 Open Loop Data Table

Freq.	V_1/cm	V_1	V_2/cm	V_2	A_v	θ
1 Hertz						
3 Hertz						
5 Hertz						
10 Hertz						
15 Hertz						
25 Hertz						
40 Hertz						
60 Hertz						

Fig. 12-19 Closed Loop Data Table

EXPERIMENT 13 Name ______________________

Date: ______________ Class __________ Instructor ______________

EXPERIMENT 14 Name ____________________

Date: ____________________ Class ____________ Instructor ____________________

S	e_1	e_o	e_f	A_u
500				
1000				
1500				
2000				
2500				
3000				

(A)

S	e_1	e_o	e_f	A_u
500				
1000				
1500				
2000				
2500				
3000				

(B)

S	e_1	e_o	e_f	A_u
500				
1000				
1500				
2000				
2500				
3000				

(C)

S	e_1	e_o	e_f	A_u
500				
1000				
1500				
2000				
2500				
3000				

(D)

S	e_1	e_o	e_f	A_u
500				
1000				
1500				
2000				
2500				
3000				

(E)

S	e_1	e_o	e_f	A_u
500				
1000				
1500				
2000				
2500				
3000				

(F)

Fig. 14-11 The Data Tables

EXPERIMENT 15

Name ______________________________

Date: ____________________ Class ____________ Instructor ____________

T	e_1	t	E	I	h

(A)

T	e_1	t	E	I	h

(B)

T	e_1	t	E	I	h

(C)

Fig. 15-7 The Data Tables